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NATIONAL WEATHER SERVICE

INTRODUCTION TO WEATHER RADAR

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U.S. DEPARTMENT OF COMMERCE
Frederick B. Dent, Secretary

National Oceanic and Atmospheric Administration
Robert M. White, Administrator

National Weather Service
George P. Cressman, Director

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PREFACE

This study material is designed for employees at Weather Service offices that have local warning radars, or have a remote radar display from Weather Service or military weather radar sets. The information contained herein is considered the minimum necessary to make intelligent use of radar weather information. Federal Meteorological Handbook No. 7, Weather Radar Observations, Parts A, B, and C provides much of the course material, and it is considered essential that local radar users and remote display users become familiar with that manual. A bibliography is provided in the manual, and Weather Service personnel may obtain desired additional reading materials from the Atmospheric Sciences Library at Weather Service Headquarters. This course of study is intended to be dynamic, with improvements and additions incorporated from time to time.

It is anticipated that the various regional headquarters may wish to require additional study by personnel in their respective regions. In such case, this volume should be considered as Part I of the study guide, and any material added by a region as Part II.

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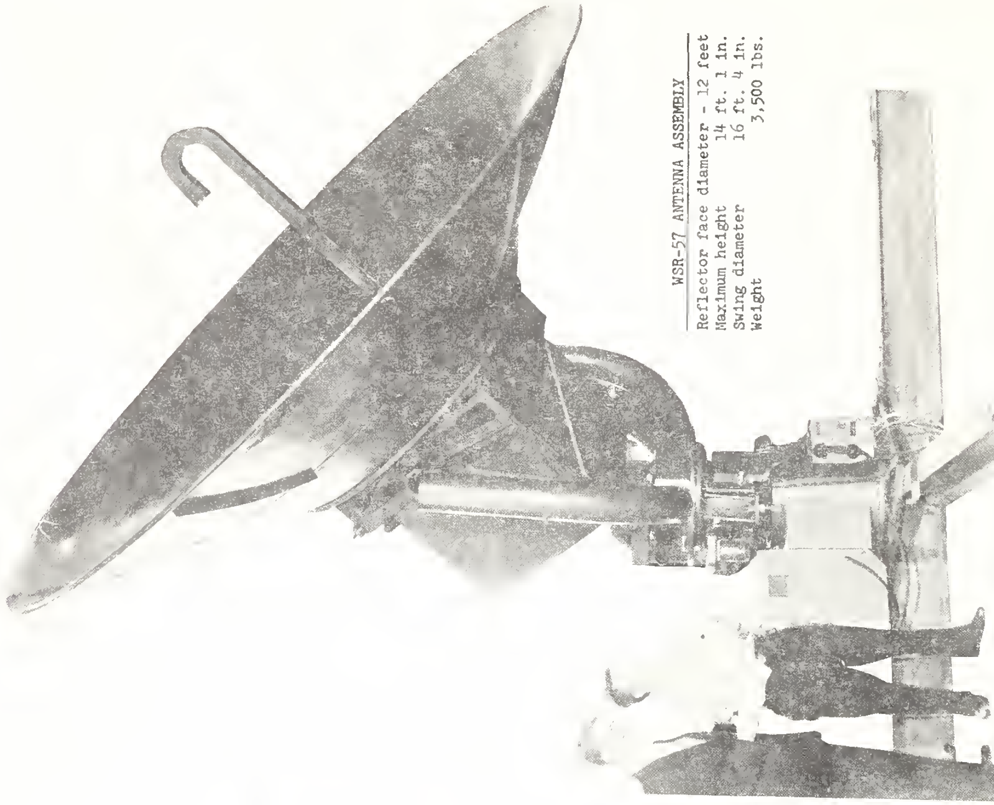
1. INTRODUCTION

The first general use of radar was to detect aircraft and surface ships during World War II. With this use in mind, weather was considered a nuisance because it sometimes produced on the radar scopes large echo patterns that made detection of aircraft or ships difficult or impossible. While every effort was made to minimize weather echoes on the military sets, it was early recognized that the weather information attainable by radar would be an important supplement to standard weather observing techniques provided we could properly analyze and define the weather echoes.

In 1947 the Weather Service began installing converted military radars, primarily in that section of the Nation most frequently subject to tornado activity. Because of their low power, relatively poor beam characteristics, and lack of objective intensity measuring capability, these radars were considered an interim substitute to be used until a radar specifically designed for weather detection became available. In 1959 the WSR-57 (Weather Surveillance Radar-57) became available, and a nationwide radar network is being developed around this powerful, sensitive radar. Provided with circuitry modifications as new technology develops, this fine radar should be the "standard" for many years. These radars are manned 24 hours a day by radar observers trained to operate the sets, evaluate the echo display, and disseminate weather information obtained from the displays. The WSR-57 radars serve the tornado country of the Midwest, the hurricane-vulnerable Gulf and Atlantic Coasts, and the flash flood areas of the Appalachian Mountains. Additional limited observations are made by NWS personnel using radar displays at four FAA Air Control Centers in the mountainous regions of the West.

The NWS operates local warning radars used on an as-needed basis to detect and track severe local storms over areas not adequately covered by the basic network radars. Many of these radars are obsolete, modified World War II surplus equipments. Modern local warning weather radars are being installed to provide more accurate measurements of severe local storms. These new, low-maintenance equipments also reduce operating costs and ensure availability when needed.

Currently, dissemination of the radar data is made using teletypewriter circuits, a composite radar summary facsimile chart and radar remoting equipment (WBRR). The WSR-57 console and antenna are shown in figure 1.


WSR-57 ANTENNA ASSEMBLY
Reflector face diameter - 12 feet
Maximum height 14 ft. 1 in.
Swing diameter 16 ft. 4 in.
Weight 3,500 lbs.

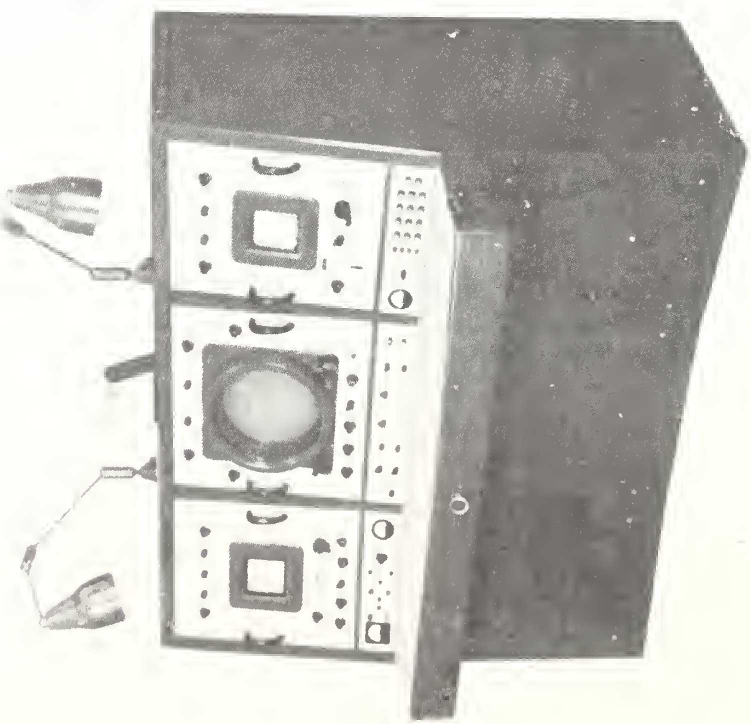


Figure 1

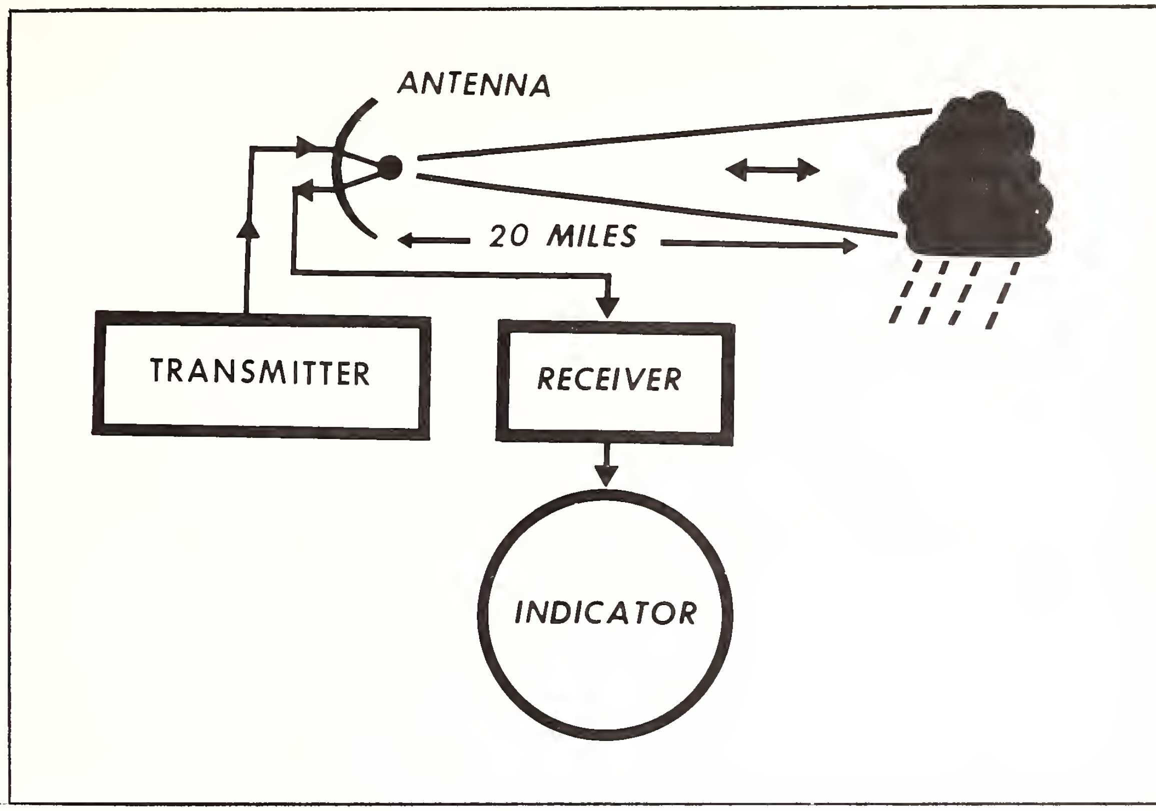


Figure 2

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2. FUNDAMENTALS OF THE EQUIPMENT

2.1 COMPONENTS

An understanding of how radar works is essential to an understanding of what is displayed on a radarscope. A radar consists of four main parts: (1) a transmitter, (2) an antenna, (3) a receiver, and (4) an indicator. The transmitter converts power supplied to the set into radio energy of a given frequency and transmits it to the antenna. A single antenna reflector serves for both transmitting and receiving the energy waves. The antenna reflector, usually simply referred to as the "antenna," focuses the waves into a narrow beam that can be rotated freely or pointed in a specific direction. The waves are reflected by the target as shown in figure 2, and sent to the receiver for detection. The receiver amplifies the signal from the antenna, and feeds the amplified signal to the indicator. The indicator converts the signal into a form that can be interpreted, usually a visual display on a cathode-ray tube.

2.2 DETERMINING DISTANCE AND DIRECTION

A radar is essentially a sounding device that emits a short burst, or pulse, of electromagnetic energy and "listens" for the return of the pulse. The electromagnetic energy travels at 161, 800 nmi per second and is scattered in all directions by objects it encounters, provided the objects are of sufficient size in relation to the wavelength of the energy. Only a small portion of the scattered energy returns to the antenna. Since distance is a product of speed and time, we can easily determine the distance of a reflecting object by measuring the time required for a pulse of energy to return to the radar. Direction is determined by focusing the radar energy into a narrow cone such as a flashlight beam.

2.3 PULSE REPETITION FREQUENCY AND PULSE LENGTH

Through the use of a very rapid electronic switch a single antenna can be used for both the transmitter and receiver, and in practice hundreds of pulses are emitted every second, with a "listening" period between pulses. Pulse repetition frequency (PRF) is an important characteristic, since it determines the maximum range of the radar. A low PRF is required for long-range detection. Another important characteristic is pulse duration. A pulse of long duration will detect a weaker precipitation target than a short pulse, but the short pulse provides better resolution. Weather Service radars have two modes of operation, providing one combination of PRF and pulse length for long-range detection of weak targets, and another combination for improved definition. Ordinarily the radar is operated in the long-pulse mode, but it may be operated on short pulse at the radar observer's discretion. Table I shows the PRF and pulse duration, as well as other pertinent information, for various radars commonly used for weather detection.

Table I. Characteristics of Weather Radars

Type	Primary user	Wave-length	Pulse Duration and PRF	Peak Trans-mitted Power	Type of antenna	Beam Width	Type of Sweep	Presentation	PPI Range	Ranging Accuracy
WSR-57 FPS-41	NWS Navy	10.3 cm	0.5 μsec--658 pps 4 μsec--164 pps	410 kw	12' parabola	2°	Automatic and manual in horizontal and vertical, either direction	PPI, off-center, PPI, RHI, R, A	250 nmi	±0.5%
*CPS-9	AF	3.2 cm	0.5 μsec--931 pps 5 μsec--186 pps	220 kw	8' parabola	1°	Manual and automatic in horizontal and vertical, either direction. Sector scan in both planes.	PPI, off-center, PPI. RHI, R, A	400 smi	±0.1 mi.
FPS-106 FPS-81 FPS-77V	Navy Navy AF	5.3 cm 5.4 cm	2 μsec-324 pps	300 kw 250 kw	8' parabola	1.6°	Automatic and manual in azimuth and elevation 5 rpm.	PPI, R, A, RHI	200 nmi	±0.5% at maximum range.
*WSR-1	NWS	10 cm	1 μsec--650 pps 2 μsec--325 pps	60 kw	6' parabola	4°	Automatic, 12 rpm, manual control of antenna tilt.	PPI, A	180 nmi	±1 mi.
*WSR-3 *WSR-4	NWS	10 cm	1 μsec--650 pps 2 μsec--325 pps	60 kw	6' parabola	4°	Automatic, variable speed to 12 rpm, reversible, automatic & manual control of antenna tilt.	PPI, A, RHI	180 nmi	±1 mi.
*Decca-41	NWS	3.2 cm	0.2 μsec--250 pps 2 μsec--250 pps	30 kw	2.6' high 14' wide	2.8° vert. 0.6° horiz.	Automatic, 5 rpm, manual elevation.	PPI	250 nmi	±1%
WSR-S1	NWS	5.4 cm	3 μsec--320 pps	250 kw	6' parabola	2.0°	Automatic and manual in horizontal and vertical, either direction. Gyro stabilized antenna.	PPI, RHI, R, A	250 nmi	±0.5%
MR-782	NWS	5.4 cm	2 μsec--250 pps	250 kw	8' parabola	1.5°	Automatic and manual in horizontal, manual in vertical, either direction.	Combined PPI/RHI	250 nmi	±0.5%
WR-100-5	NWS	5.4 cm	3 μsec--320 pps	250 kw	8' parabola	1.5°	Automatic and manual in horizontal, manual in vertical, either direction.	PPI, RHI, R, A	250 nmi	±0.5%
WSR-74	NWS	5.4 cm	3 μsec--266 pps	250 kw	8' parabola	1.5°	Automatic and manual in horizontal, manual in vertical, either direction.	PPI, RHI, R, A	250 nmi	±0.5%
FPS-20 FPS-67	AF FAA	23 cm	6 μsec--360 pps	5,000 kw	40' wide 16' high	1.3° azi. 22° vert.	Automatic in azimuth	PPI	250 nmi	±1 mi.
ARSR-1E	FAA	23 cm	2 μsec--360 pps	5,000 kw	40' wide 11' high	1.35° horiz. 6.2° csc^2 vert.	Automatic PPI.	PPI	250 nmi	±1%
ARSR-2	FAA	23 cm	2 μsec--360 pps	5,000 kw	47' wide 23' high	1.2° horiz. 3.75° vert.	Automatic PPI.	PPI	250 nmi	±1%
FPS-103	AF	3.2 cm	2.5 μsec--400 pps	50 kw	2.5 parabola	3.6°	Automatic in horizontal 15 rpm. Manual in vertical.	PPI	150 nmi	±1%
WSR-75	NWS	10.3 cm	1 μsec--545 pps 4 μsec--164 pps	556 kw	12' parabola	2.2°	Automatic and manual in horizontal, manual in vertical, either direction	PPI, RHI, A	250 nmi	±0.5%

*Obsolete

2.4 MAXIMUM RANGE

The maximum range of a radar, aside from the geometric considerations to be discussed later, is determined by the pulse repetition frequency of the radar. The energy return from a number of pulses is required in order to display an echo on the scope, so it is desirable that as many pulses as possible reach the target. However, since each pulse must travel to the target and back to the antenna before the next pulse is emitted, too high a PRF would severely limit the maximum range of the radar. The choice is a balance between these considerations. When pulse lengths are short for greater definition, it is necessary to get more hits on the target in order that a detectable signal is returned to the radar, and a high PRF is used, limiting the radar's range. In the case of a WSR-57 operating in short-pulse mode, the pulse has only sufficient time to reflect from a target up to 148 nmi range and return to the antenna before the next pulse is emitted. In long pulse mode, there is sufficient time for the pulse to travel 493 nautical miles and return before the next pulse is transmitted. Because of the curvature of the earth, the radar beam is usually well above any weather targets at such extreme ranges, and scope displays are therefore limited to the practical value of 250 nmi.

2.5 RESOLUTION

Resolution describes the ability of the radar to show discrete targets separately. There are two distinct resolution problems: (1) range resolution (the ability to distinguish between two targets at the same azimuth but at different ranges) and (2) beam width resolution (the ability of the radar to distinguish between two targets at the same range but at different azimuths). Since it can be shown that the range resolution of a radar is half the pulse length, the WSR-57 cannot distinguish between objects less than 600 meters apart in range when in the long-pulse mode, of less than 75 meters apart when in the short-pulse mode. Beam width resolution is a function of the size and shape of the radar beam, and therefore, the beam width resolution capability of the radar varies inversely with range of the targets. Any target, regardless of how much of the beam it fills, that reflects to the antenna a detectable signal will be displayed on the scope as being at least as large as the beam width in one dimension, and as large as the pulse length in the other dimension. Since the beam width increases at greater ranges, targets at greater ranges must be separated by greater distances in order to appear as separate targets on the scope. An important implication here is the increased beam width distortion, or stretching at right angles to the beam, as distance from the radar increases. Figure 3 illustrates resolution.

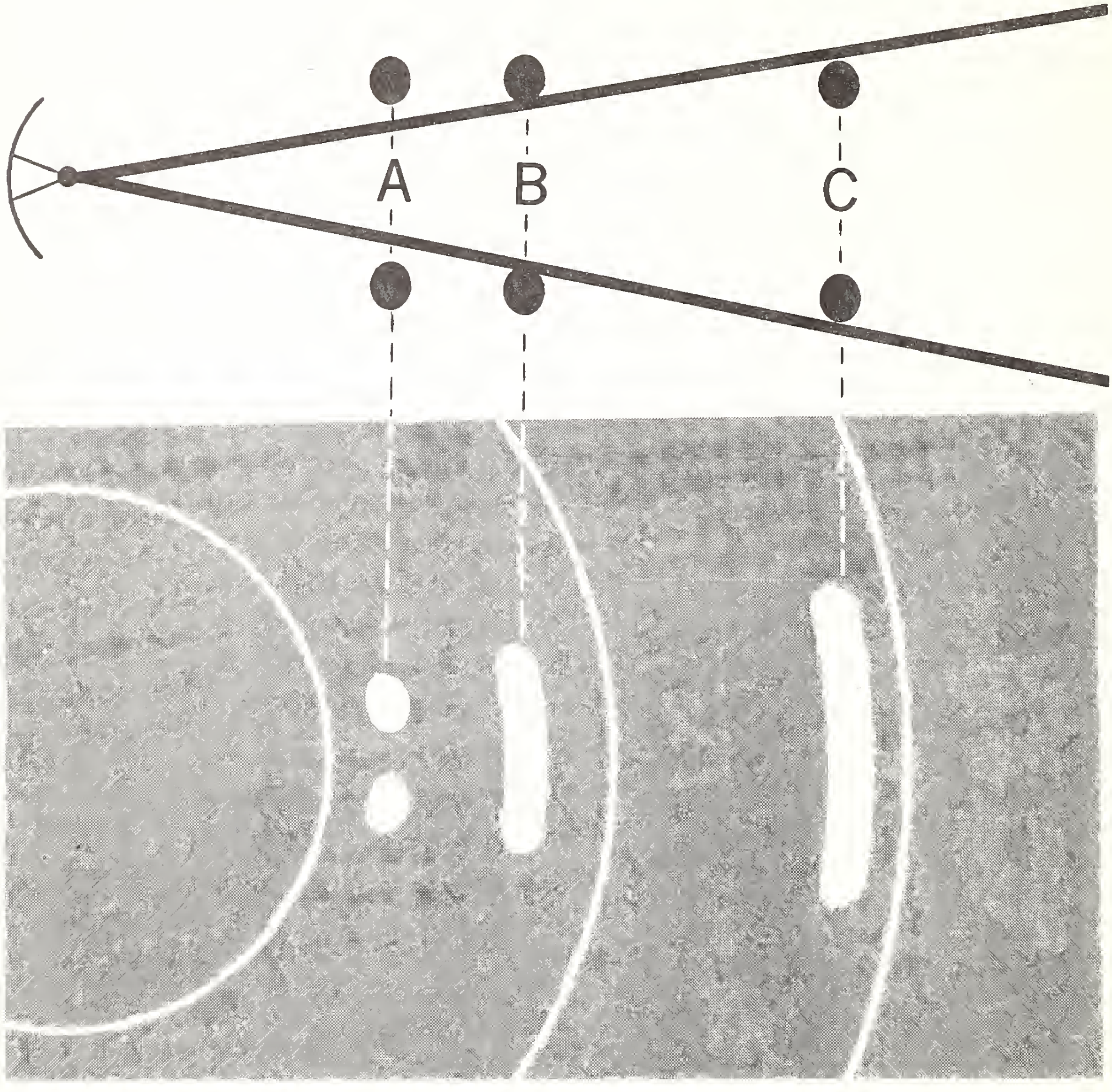

Figure 3. This figure is exaggerated in order to easily illustrate beam-width resolution and beam-width stretching. The targets at range A would both appear on the scope only if the beam were rotating. Neither would appear on the scope if the beam were stationary as shown. The targets at range B are the same distance apart as those at range A, but appear on the scope below as one echo because they are not separated by a beam width. The targets at range C are also the same distance apart, but the echo appears larger because of beam width stretching.

2.6 THE RADAR BEAM

The shape of a radar beam is determined by the shape and size of the antenna reflector as shown in figure 4. The WSR-57 antenna reflector is a paraboloid 12 feet in diameter, concentrating the radar energy in a conical beam with an angular width of 2 degrees. The reflectors on WSR-1 and WSR-3 radars are 6 feet in diameter, and produce a 4-degree beam. Radars designed for other purposes may have a differently shaped beam, as illustrated in figure 4. The beam of a radar set is difficult to define precisely and an arbitary, but very useful, definition is agreed upon. That locus of points around the axis of the beam where the beam energy has decreased by 50 percent from the theoretical maximum along the beam axis is considered the edge of the beam. This does not mean, however, that any given target will always appear on the scope if within the beam as defined here, or will never appear on the scope if outside the beam. An easy, although not exact, illustration of this can be made with a flashlight beam. Many flashlights produce a visible narrow conical beam, yet also illuminate objects outside this cone. A small object is easily identifiable over a wide angle at very close range but must be within the beam to be seen at greater distances, and as the range increases even further the object is not identifiable even though still obviously near the axis of the beam. In the case of radar as with a flashlight, it has been found that there are secondary maxima of energy radiated outside the primary beam, and targets illuminated by these secondary lobes sometimes return enough energy to be detected and displayed on the scope. The radar, however, cannot display except along the beam axis, and will present the target along that axis at a range corresponding to elapsed time between pulse emission and echo return. Thus an echo may appear on the scope in a position that corresponds to a geographical location where there is actually no target. These side-lobe echoes are usually at close range and frequently are masked in the ground clutter around the center of the scope.

2.7 MULTIPLE-TRIP ECHOES

A radar always displays echoes as if any signal return is assumed to be from the last emitted pulse. Therefore, if a reflected signal from a previous pulse is detected it will be erroneously displayed on the scope as a target much closer to the radar than is the actual case. This can happen fairly easily in the case of short pulse operation, where maximum displayable range is 125 nmi (WSR-57), because the signal energy is still strong enough to illuminate targets beyond that range, and the beam is still low enough to intercept numerous targets. Multiple-trip echoes occur infrequently when the radar is in long-pulse mode. Such echoes may occur during conditions of super-refraction, and ordinarily disappear if the antenna is pointed slightly upward. The range to a target producing a multiple-trip echo may be determined by $R=n(mr)+r$, where n=number of pulses removed from latest (usually one), mr=maximum range as determined by PRF, and r=range of echo as displayed on the scope.

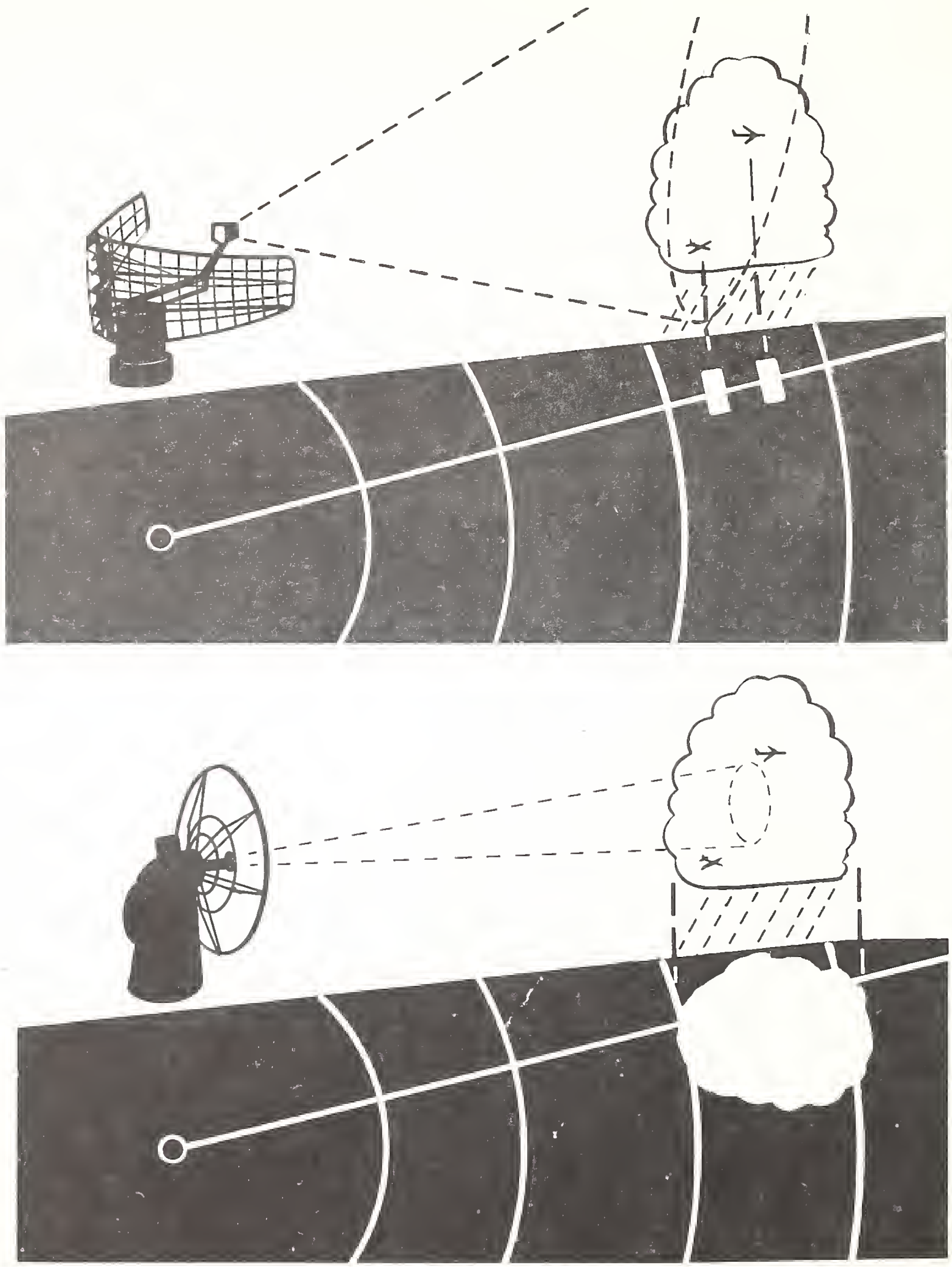

Figure 4. Air traffic control radar is used to detect all aircraft regardless of altitude. It must scan all airspace within its range with each rotation of the antenna. It has a beam narrow in horizontal dimension but wide in the vertical dimension (fan shaped), as shown in the top picture. The bottom picture illustrates what a weather radar might see. A height-finding radar on the other hand, which requires accurate vertical angle measurements, also has a fan-shaped beam but with the narrow dimension being vertical.

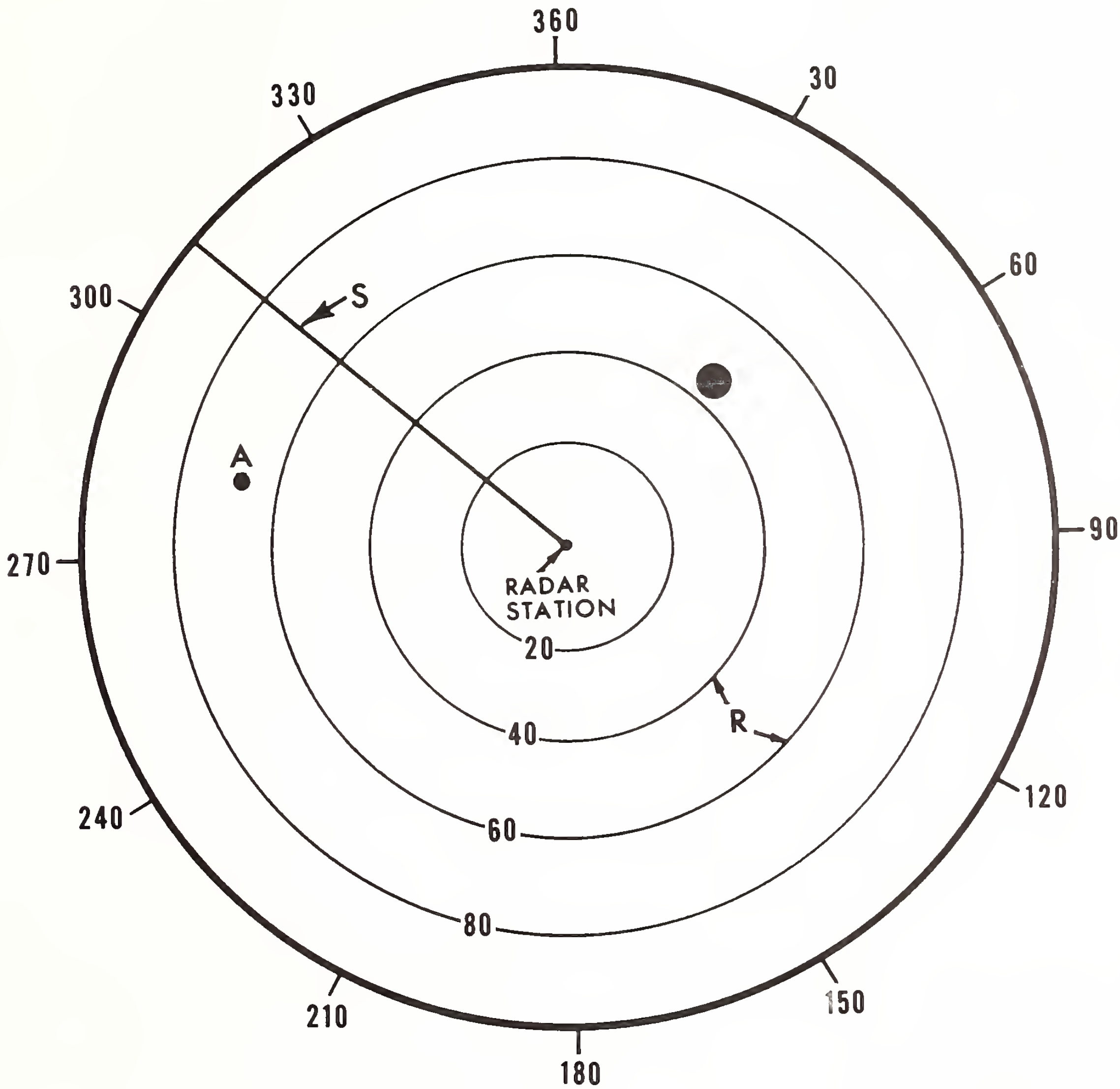

Figure 5. PPI scope. The center of the display represents the location of the antenna. A sweep line, labeled "S" is synchronized to rotate with the antenna. As the antenna and sweep line rotate, a picture, or map, of the targets is displayed on the scope. The markings around the edge of the PPI are bearings, or azimuth markings, in true degrees from the antenna. On this scope the echo in the upper right is at an azimuth of 40 degrees and a range of 45 nautical miles. Range markers, labeled "R" are added electronically to the PPI, denoting distance from the antenna in nautical miles.

The radar observer will omit multiple-trip echoes from radar weather reports. This is one of several reasons why it is necessary to use RAREPs in conjunction with a repeater scope display. Second trip echoes will appear on a repeater display, and may be difficult to distinguish without other information. See figure 11.

2.8 SCOPE DISPLAYS

The viewing scopes of a radar are cathode-ray tubes similar to an ordinary television tube. The major difference is in the phosphers of the mapping scopes, which have greater retention qualities that allow the echoes to remain visible until the next sweep of the antenna.

2.8.1 PLAN POSITION INDICATOR (PPI)

The Plan Position Indicator plots direction versus distance on polar coordinates, with the radar location at the center. Image retention is on the order of 20 seconds. Several different range settings are available, at the option of the operator, and the WSR-57 has an additional off-centering device that allows any portion of the PPI display to be selected for centering and enlargement. Evenly spaced range marks appear on the PPI when the scope is normally centered and operating in standard range increments. Figure 5 illustrates features of the PPI. The image of the PPI scope is the one transmitted on the WBRR but the rotating sweep will not be apparent. Also, the WBRR transmission will not include off-centering display, and it will have only three possible scope range displays, i.e., 50 nmi, 125 nmi, and 250 nmi. WBRR users should be aware that scope display versatility at the radar site is greater than at the WBRR display.

2.8.2 RANGE HEIGHT INDICATOR (RHI)

The Range Height Indicator displays range versus height. Since the antenna tilt remains constant for normal search sweeping, this scope usually does not display a picture. The antenna can be made to tilt, however, and if horizontal rotation is stopped and a complete vertical sweep made a vertical profile of echoes will be displayed on the RHI. The WSR-1 has no RHI, but does have a vertical angle indicator to help determine heights. The WSR-3 PPI can be switched to display RHI instead of its usual picture. The maximum range that can be displayed on the WSR-57 RHI has been selected to be 125 nmi because of increasing beam width and altitude at greater ranges, and because non-standard atmospheric refraction of the beam introduces uncertainties in indicated echo altitude. Image retention is on the order of 20 seconds. Note that the range and height scales are not the same, and thunderstorms have the appearance of being tall and thin when actually they are shaped somewhat like a rosebud. The RHI image is not transmitted on the WBRR, but RHI information is included in WBRR scope annotations. RHI scope display is shown in figure 6.

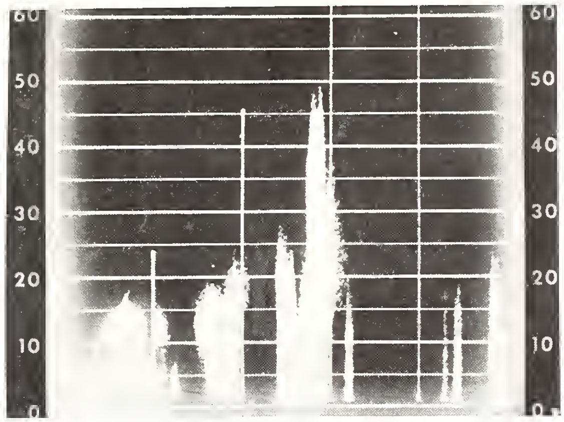

Figure 6. Convective rain cells as shown on RHI. Horizontal lines indicate altitude in thousands of feet. Vertical lines are range markers, in this case 20 miles apart.

2.8.3 A- AND R-SCOPES

The A-scope plots range versus intensity of signal return. It does not give a picture of the size and shape of the target, but is very useful to the radar observer in determining exact ranging and strength of the return, and very importantly, in determining the character of the return. Objects such as buildings, aircraft, and precipitation can be identified by the signatures they present on the A-scope. On the WSR-57, any portion of the A-scope can be selected for expanded presentation on the cathode-ray tube, and this usage is called the R-scope.

2.9 WEATHER BUREAU RADAR REMOTE (WBRR)

The WBRR is designed to provide annotated PPI display at locations remote from the radar position. It scans the picture slowly so that the many information bits in the picture can be transmitted over regular telephone line, thus avoiding the expense of coaxial cable or a microwave transmission system. Tests have shown that randomly selected telephone lines are suitable for transmission of the WBRR picture, making it possible to "dial-up" a picture from any radar properly equipped, regardless of the distance. Thus, radarscope data will be immediately available to not only those selected weather service offices under the radar umbrella that have a direct hookup, but to any interested forecast office. Figure 7 illustrates the WBRR system.

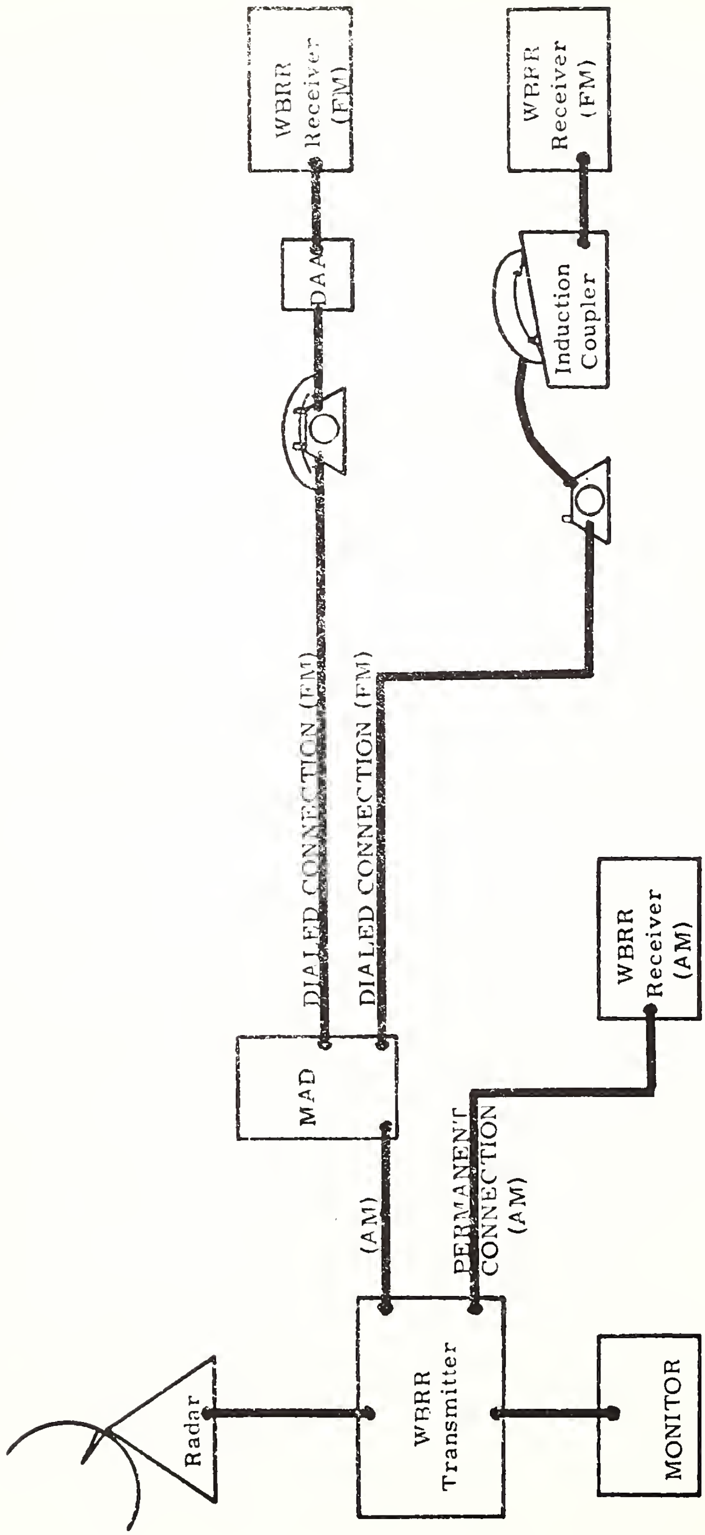

Figure 7. The WBRR System

In 1965, the first NWS radar remoting system utilizing telephone lines as the transmission medium was developed. This system, designated RATTS-65[1] and later WBRR-65[2], was designed to provide near real time weather radar data to WSFO's and WSO's within the effective range of the WSR-57 radar (nominally 125 nmi). The first system was installed at Galveston-Houston in December 1965. Essentially, the radar picture is transformed from rho-theta to a rectilinear display with a vidicon TV camera, transmitted over 3-kHz telephone lines at a rate of 1 frame every 100 seconds and, in the RATT-65 or WBRR-65 system, displayed on a storage tube at the receiver location. From each receiver location, the picture can be transmitted to as many as six 14-inch CRT display monitors. A unique feature of the system is that the radar observer can add remarks pertaining to echo features which are superimposed, with a map of the area, on the radar display using a data insertion device. A telephone hot line is also provided linking the radar operator to the user office. Most of the WBRR systems are connected to radars which have the Video Integrator and Processor (VIP). This device provides up to six contours of echo intensity (rainfall rate). In 1968, the system was modified to utilize a facsimile recorder at the receiving end, which would provide a record of the display rather than the perishable TV picture. The facsimile system is designated WBRR-68.

There are two primary types of WBRR transmitter-to-receiver links: dedicated line and dial-in. The dedicated line provides continuous access to the radar and is mandatory where the radar remote is used extensively in the severe local storm forecast and warning program. Recorders connected to dedicated lines are usually well within 75 nmi of the radar to provide good coverage at reasonable cost. The dial-in capability is used when occasional pictures from different radars are useful; for example, at a WSFO or a centralized facility, such as the FAA's Central Flow Control Facility. All transmitters are now equipped with multiple access devices (MAD) which permit simultaneous calls to one transmitter. There is no mileage limit to the call, which is charged at the usual long-distance rate. Two complete pictures are received before the transmitter automatically disconnects. If the radar picture is unavailable (due to stoppage of antenna rotation, for example), the transmitter will not answer. All NWS recorders are now equipped with dial-in capability. In addition, there are other government and many non-government users.

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[1]Radar Telephone Transmission System

[2]Weather Bureau Radar Remote

2.10 VIDEO INTEGRATOR AND PROCESSOR (VIP)

INTRODUCTION

The Video Integrator and Processor (VIP) is an adjunct of the WSR-57 radar system. It has been developed to meet both present and anticipated requirements for continuous quantitative data output for (1) console presentation, (2) dissemination by remoting systems such as the WBRR-68, (3) photographic data recording, and (4) further processing using computer techniques. The VIP automatically processes the output of the radar's logarithmic receiver to produce up to six levels of intensity data corresponding to pre-selected categories of estimated rainfall rates. These levels may be displayed individually or simultaneously on the radarscope. This will permit the constant monitoring of echo intensities, within these categories, with each rotation of the antenna.

MODES OF OPERATION

There are two basic modes of operation designed into the VIP: (1) the contoured log (C-log) and (2) log. The C-log mode can be used to present up to six levels of intensity according to table II.

The log mode presents the output of the logarithmic receiver without contours. This mode may be used on all ranges; however, the C-log is presently limited to 125 nmi or less.

Whenever the linear receiver of the radar is used, the VIP does not affect the scope displays in any way.

VIP CONTROL FUNCTIONS

The VIP is designed to be operated full time. The OFF-ON switch is located on the back of the cabinet. In order for the VIP calibration to be valid, the radar must be operated in the log receiver mode at 3 rpm, in long pulse, with STC OFF. The mode of operation is selected by using either the log or C-log push button switch on the right side of the VIP cabinet face. In the C-log mode, combinations of levels may be selected by using the level selector push button switches on the left of the cabinet face. Each of these six switches has an indicator light just above the switch. These lights are energized as the signal passes each level and remains on for 20 seconds (one rotation of the antenna at 3 rpm). A quick glance at these lights near the end of each rotation will reveal the highest level signal for that rotation of the antenna.

Table II. VIP Intensity Levels

Level	Display#	Rainfall Category	Rainfall Rate (in./hr., lower level)	LOG Z	Pr*
1	gray	light	<0.1		<-99.5
2	white	moderate	0.1-0.5	3.0	-88.0
3	black	heavy	0.5-1.0	4.1	-77.0
4	gray	very heavy	1.0-2.0	4.6	-72.0
5	white	intense	2.0-5.0	5.0	-67.5
6	black	extreme	>5.0	5.7	-61.0

#Refers to radar PPI. White and black are reversed on WBRR.
*Equivalent received power using the LIN receiver. The actual signal generator values used to set up the VIP thresholds are 2.5 dB lower than these values, for example -90.5 dBm rather than -88 dBm in the case of level 2.

OPERATIONAL REQUIREMENTS

Camera repeater scopes and WBRR transmitters should normally present contoured displays. This means that the radar must be operated in long pulse, and the VIP must be in C-log mode with all six levels selected for display. The radar STC must be turned off or disabled since range normalization is provided by the A-10 board which should have been installed.* The radar antenna must be allowed to rotate at 3 rpm, with tilt adjusted for precipitation detection over the optimum range. The rotation speed should be checked and adjusted during the periodical calibration check, and more frequently if necessary. If this "normal" operation is interrupted for lengthy periods, because of equipment malfunction or for any other reason, appropriate notations should be included on WBRR and camera scope displays. Whenever the normal operation is interrupted briefly, such as for echo top measurement, notations are not necessary. In either case, the normal operation should be resumed as soon as possible.

*All levels except level 1 are range normalized. Level 1 is not range normalized so that all detectable light precipitation will be displayed as level 1.

OBSERVATION TECHNIQUES

The VIP facilitates the recording of radar reports (SD) and narrative reports because it displays on a single sweep a contoured picture which, if constructed by attenuators and grease pencil, would be several minutes in the making. The following observational procedure is suggested:

After determining that the radar is delivering standard performance, set the radar console PPI to 250-nmi range (C-log cannot be used for this display)* but do not interrupt C-log VIP mode service to remote displays. If there are echoes beyond 125 nmi, locate and record the areas, lines, and cells as necessary on this range setting. Switch then to the shortest range that will display all the echoes within 125 nmi, and switch the main PPI to the VIP C-log display. Manipulation of the level selector switches will allow determination of maximum intensities and characteristic intensities as reported in SD's and narrative summaries. Note that the normal antenna rotation is not interrupted, and that remote displays can be served with C-log VIP mode while the main PPI is adjusted to the 250-nmi range. It will be necessary to stop the normal antenna rotation in order to determine vertical configuration. This should be done as necessary, but on a scheduled basis as much as possible. Top measurements may be made within the lin receiver, or with the VIP in C-log mode.

*A modification is being developed to permit C-log VIP operation on 250-nmi range; contours would only appear to 125 nmi, and normal echo presentation beyond 125 nmi.

2.11 REQUIRED STUDY

FMH No. 7, Part B, Chapter 1.

FMH No. 7, Part C, Section III.

3. FUNDAMENTALS OF RADAR PROPAGATION AND DETECTION

3.1 PROPAGATION

Electromagnetic waves emitted by a radar travel in a straight line when in a vacuum or in a medium homogeneous in density and composition. The more dense the medium, the more slowly the waves travel. This is very significant when considering the propagation of radar waves, because of the great density variations with height in our atmosphere. Since the waves travel faster in the less dense air at greater heights the motion of a wave front is not straight, and the resultant radar beam is curved as shown in figure 8. It has been found that the amount of curvature depends on temperature and humidity lapse rates in the atmosphere, and because of the many variables involved we can never say just how great the curvature is at any given moment. In order to define a reference, a standard atmosphere is assumed such that the radar beam is considered to have a radius of curvature four times that of the earth, and the radar is calibrated to display echoes as if this were always the case. Any atmospheric variation from standard causes a nonstandard beam curvature resulting in erroneous positioning of the echo on the radar scope. The error in horizontal distance is small, but the error in height as displayed on the RHI can be considerable, especially at long range (see fig. 9). This error is not an apparent one from scope considerations alone, and without definitive information about the prevailing refractive index an accurate correction cannot be made. Because of great diurnal and areal variations with our present observing networks we cannot accurately define the horizontal and vertical variations of refractive index at any given time, but we can make gross estimates. One can imagine many possible variations in beam refraction, with the curvature changing at different altitudes and different azimuth bearings. When the beam has a curvature greater than standard, thereby remaining closer to the earth than normal, "Superrefraction" exists. If the beam is straighter than standard, "Subrefraction" exists. Figure 10 illustrates nonstandard refraction.

3.1.1 DUCTING

"Ducting" is an intense form of superrefraction occurring when the beam is trapped below an inversion. This is often the case during early morning hours when there has been good surface cooling by radiation and there is an increase in temperature and a decrease in moisture with height in the lower atmosphere. Ducting can occur in all directions from the radar, or within limited angular boundaries. Cold air outflow associated with thunderstorms sometimes causes ducting. During ducting conditions, the scope will show an enlarged ground clutter pattern and may present ground targets at great distances. Multiple-trip echoes of terrain features hundreds of miles from the radar have been identified on many occasions.

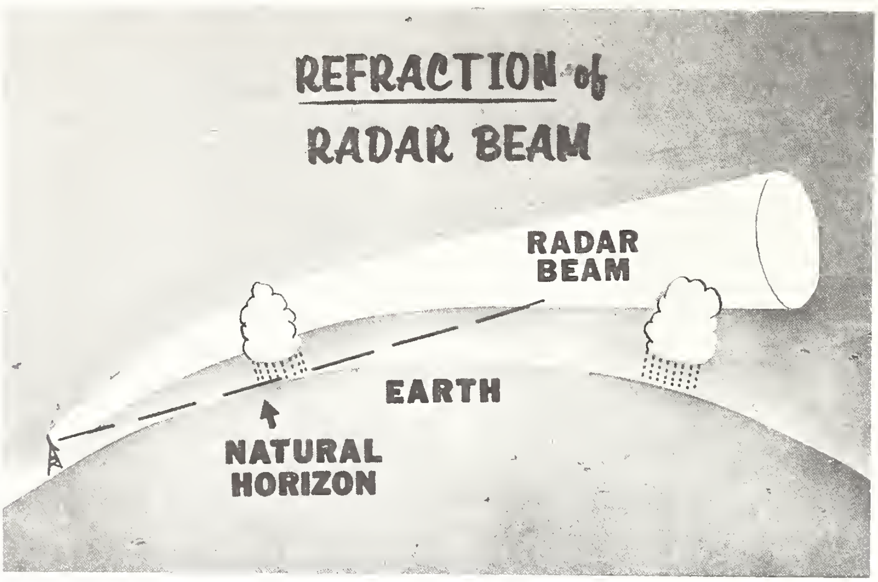

Figure 8. Since the radar beam usually is not straight, but has a radius of curvature four times that of earth (in standard atmosphere), radar can "See" beyond the visual horizon.

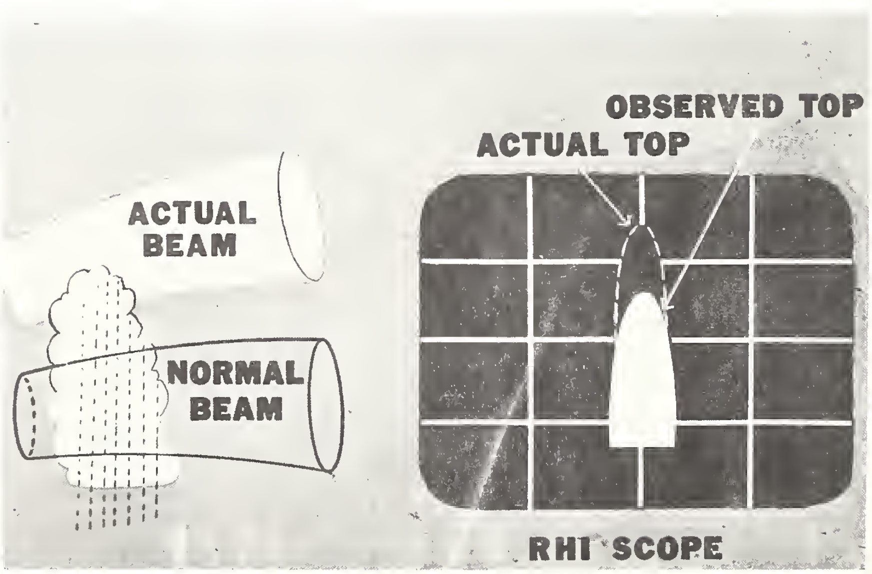

Figure 9. Heights of echo bases and tops, as displayed on the radar, are based on normal refraction. Since the radar has no way of detecting the true path of the beam, indicated heights may be erroneous.

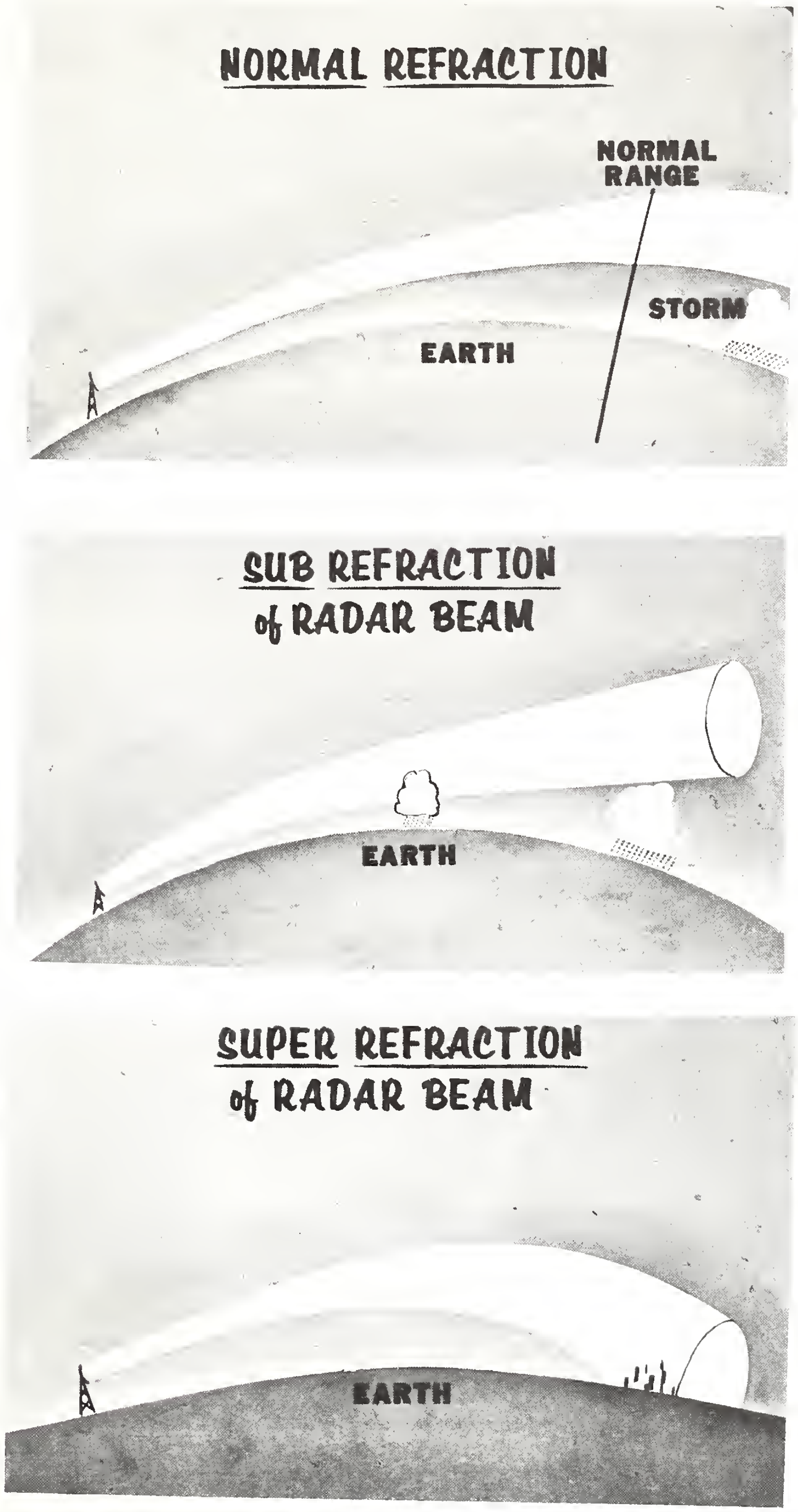
NORMAL REFRACTION
NORMAL RANGE
STORM
EARTH
SUB REFRACTION of RADAR BEAM
EARTH
SUPER REFRACTION of RADAR BEAM
EARTH

Figure 10

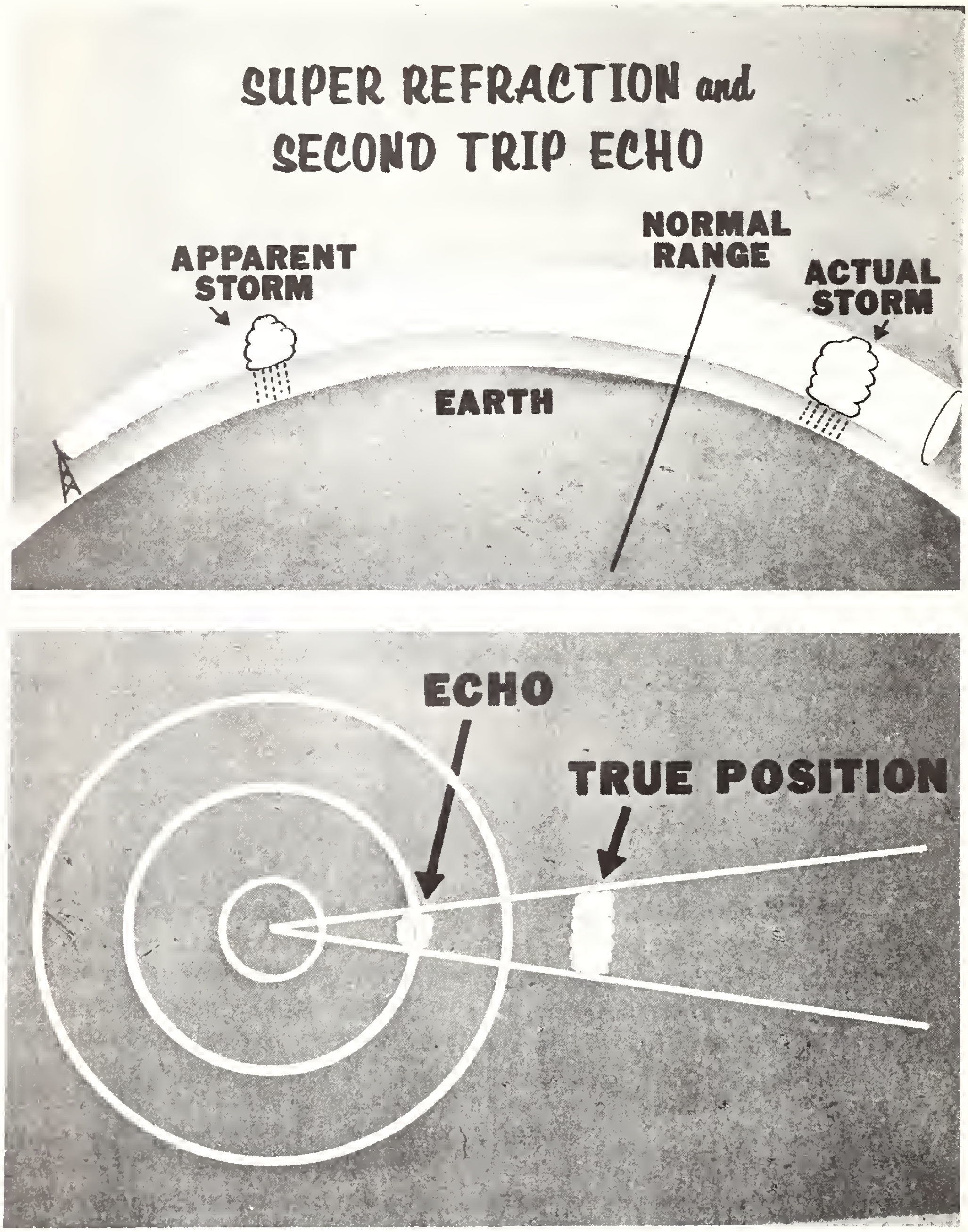

Figure 11. A combination of strong distant echoes and superrefraction may cause radar sets to detect these targets beyond the normal range. Echoes received after the next pulse is transmitted, are called "second trip echoes" (more generally "multiple-trip echoes"). These echoes are "squeezed" when displayed on the PPI because the beam is more narrow at closer ranges.

3.1.2 ANAMALOUS PROPAGATION

Extraordinary display of ground targets is often termed "AP" (Anomalous Propagation), and while it is easily identified at the radar console it may be mistaken for precipitation echoes if viewed only on the PPI. AP can appear on the scope at the same time as precipitation and may even be intermingled with precipitation, providing a time-consuming task in separating the two in radar reports. If radar reports show precipitation at locations where it is apparent through visual observation that none exists, the radar observer should be notified immediately. Figure 12 shows exceptional anomalous propagation, while figure 15 shows a more normal ground return.

3.1.3 FINE LINES AND ANGELS

Radio waves may actually reflect from layers of steep refractive index gradient, returning to the antenna either directly or after striking the ground or other objects. Thus echoes that represent neither precipitation nor ground features may appear on the scope. When the reflecting discontinuity has line form, such as at the density discontinuity at a thunderstorm wind shift line (fig. 13), the echo is called a "fine line," and is reported in the RAREP. Many times the echoes from discontinuities do not have a line form, however, and are difficult to characterize. They then usually fall into the broad category of "angels," a term used to describe echoes of unknown origin. Angels usually appear as weak and amorphous echoes, with a continually changing structure, but may at times present identifiable patterns. The term also includes return from birds and insects. Figure 14 is a good illustration of angels on the PPI. Fine lines and angels appear much more frequently on the WSR-57 than on other Weather Service radars, because of its power and sensitivity.

3.1.4 CHAFF

Chaff consists of a great many strips of metallic foil released in the atmosphere in order to create a target or interference to radars. The strips are usually cut to a length equal to one-half the wavelength of the radars concerned. The shape and size of the echo from chaff depends on the altitude at which it is released, the pattern flown by the aircraft, the amount of chaff released, and the winds in the atmosphere below the release altitude. It usually first appears as a thin band, and then spreads as it falls and drifts with the wind. It is frequently released in several parallel bands. While it can be mistaken for a weather echo, there is a difference in the characteristics of the two as seen on the A scope, and chaff usually can be observed to fall slowly. Each operator should, at the first opportunity, closely study chaff echoes so as to be able to distinguish them from precipitation. Figure 16 illustrates chaff as it appears on the PPI.

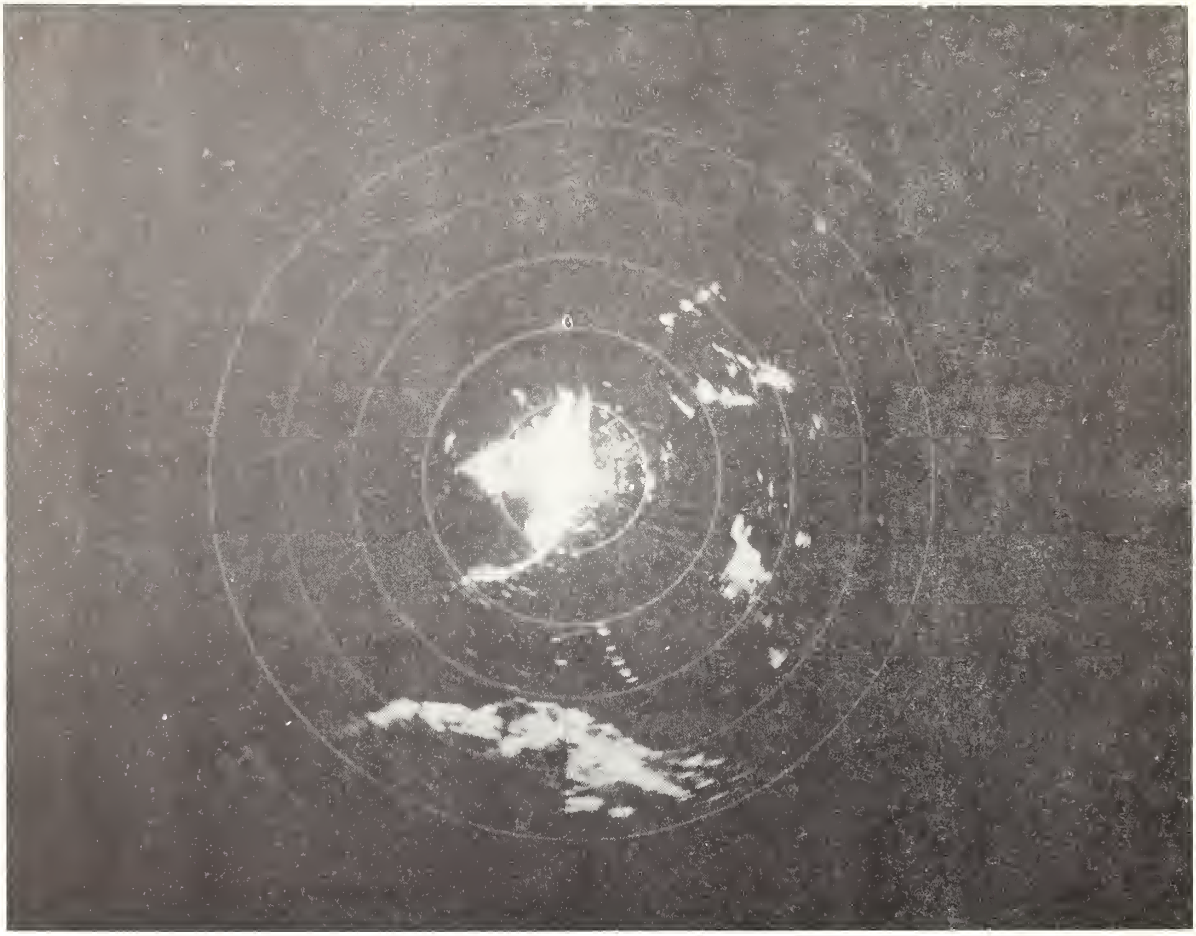

Figure 12. An extraordinary "AP" situation as photographed at the Miami WSR-57. A widespread atmospheric inversion has trapped the radar beam near the surface of the earth northeast of the radar through the south to west of the radar, and as a consequence some of the Bahama Islands, Cuba, and the Florida Keys present a detectable return to the radar. Surface heating has destroyed the inversion over most of the Florida peninsula, however, and refraction northwest of the radar appears near normal. Some of the point ranges south and east of the radar are ships, some are small islands. The scattered straight line in the northeast quadrant is a line of rain showers. The "needlework" that extends from the radar to maximum range between 100 degrees and 140 degrees azimuth is caused by radio interference in the atmosphere, likely from another radar. The range marks are 50 nmi apart. Compare this with figure 15.

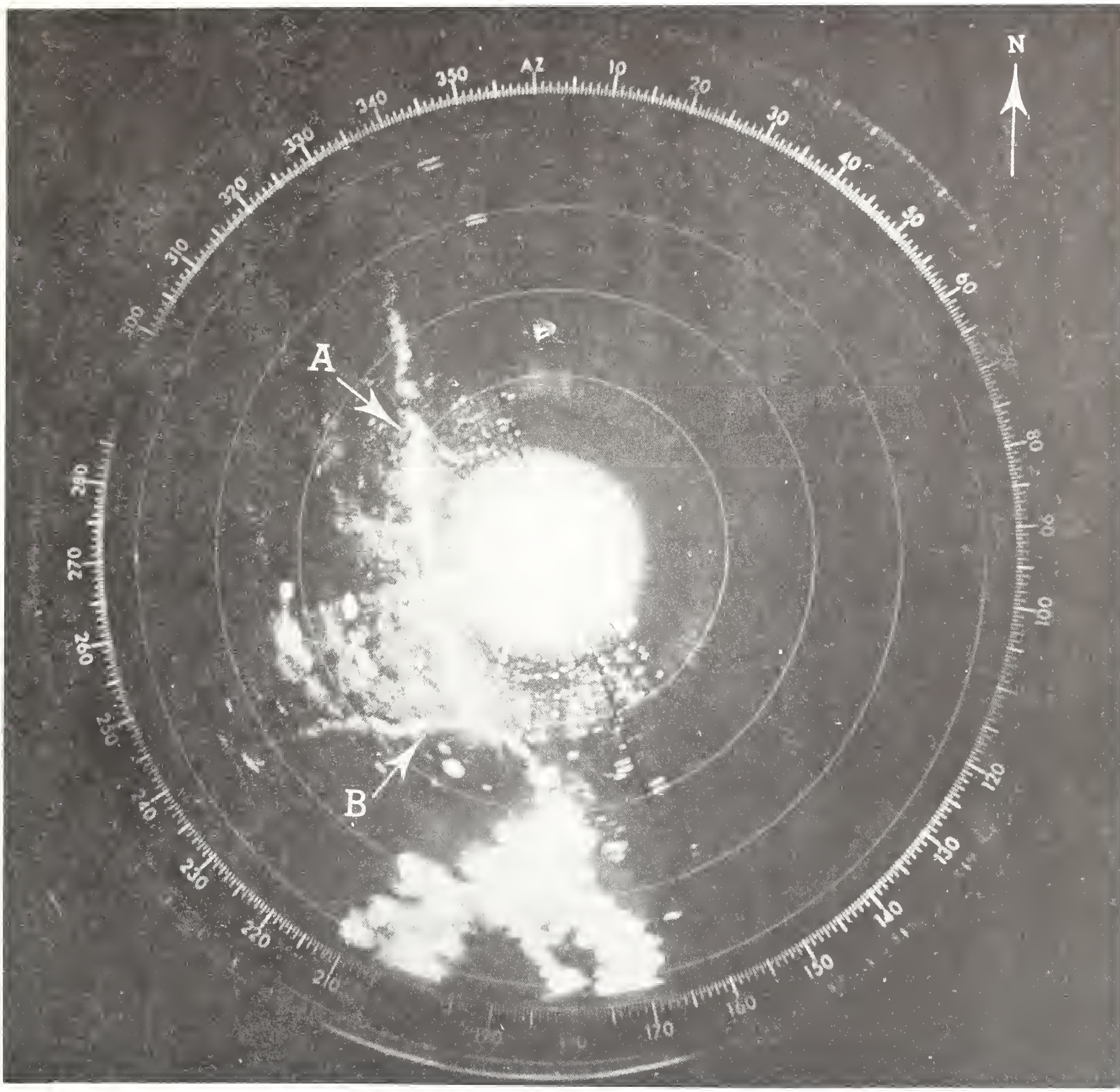

Figure 13. Fine lines as seen by the WSR-57 at Daytona Beach, Florida. The line identified by "A" is associated with the sea-breeze front existing at the time, and line marked "B" is the precursor line associated with the thunderstorm seen in the southern quadrant. Note the small showers inbedded in the ground clutter and angels between 250 degrees and 260 degrees azimuth. Aircraft targets appear double because the camera shutter was left open for two rotations of the scope sweep, thus spotting the aircraft at two different locations 20 seconds apart in time.

Figure 14. Echoes of unknown origin, or "Angels," appearing over the water east of the Miami WSR-57. Many of the small targets may be birds. Compare with figure 15. The "fuzzy" triangular shaped target at 335 degrees, 25 nmi range (edge of ground clutter) is characteristic of the echo from smoke, the fire being located at the acute angle of the echo. In this case northerly winds are indicated in the low levels. Range is 50 nmi with range marks 10 nmi apart.

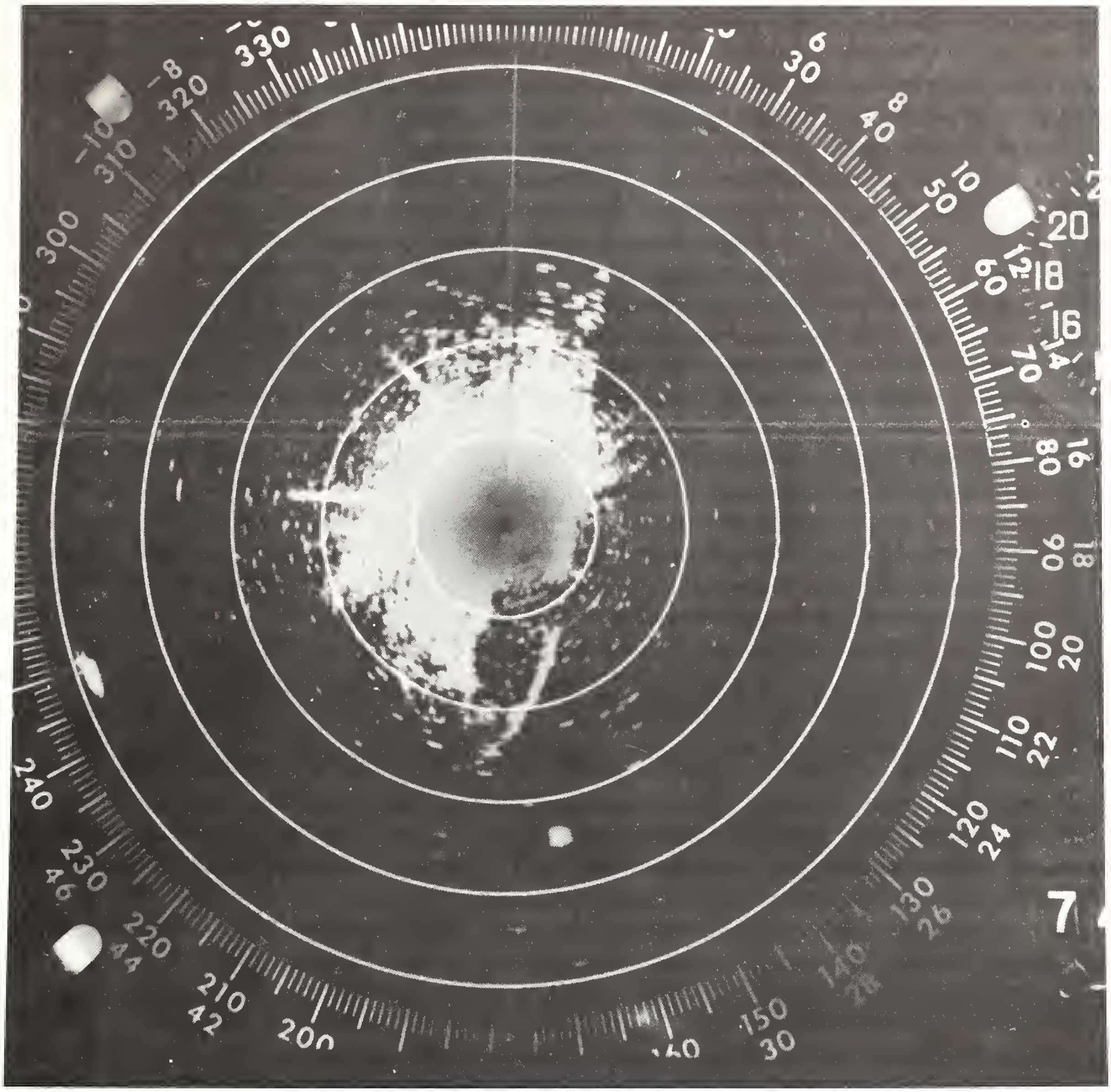

Figure 15. Ground clutter display representative of "Normal" conditions at the Miami WSR-57. Note the outline of the southern part of Biscayne Bay, and the northernmost of the Florida Keys. Terrain is very flat in south Florida, so most of the echoes in the ground clutter are from man-made objects and trees. The straight lines west and northwest of the radar are echoes from trees and powerlines along highways and canals. The isolated point targets near the ground clutter consist of aircraft, boats, isolated tall structures, and possibly even birds and insects. The more distant point targets are aircraft. There are two very small showers displayed on the scope; can you find them? Range is 50 nmi with range marks 10 nmi apart.

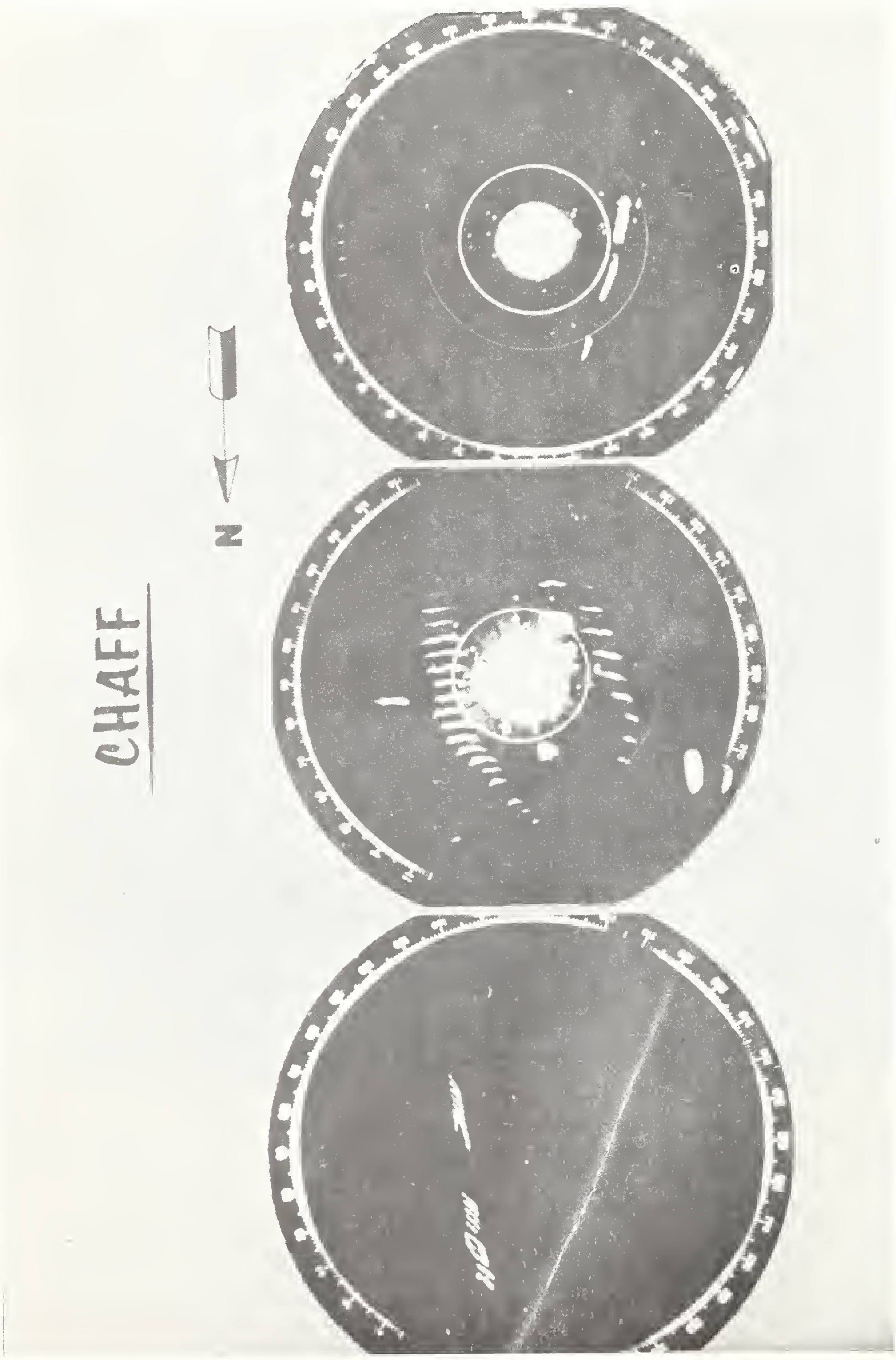

Figure 16. Chaff is strips of metallic foil dropped from aircraft, usually by armed forces, specifically to jam military radars. It usually first appears as a thin band, and then spreads as it falls and drifts with the wind. It can sometimes be easily mistaken for a weather echo.

3.1.5 REQUIRED STUDY

FMH No. 7, Part B, Chapter 2.

3.2 DETECTION

3.2.1 LARGE TARGETS

We must now consider just what a radar "sees." Obviously if the energy waves from a radar strike an object such as a building or a metal aircraft they will not penetrate but will be reflected, with some of the reflected energy returning to the radar antenna. In such a case the radar will display on the scope a target corresponding to the location of the reflecting object, but can give no further information such as areal extent and shape of the object, since the reflection is from the nearest side only. If the object subtends an angle smaller than the radar beam width, the echo will be indicated on the PPI as an arc, the dimensions of which are determined mostly by the beam width and pulse length of the radar. If the object is significantly larger than the beam width, the shape of its edge nearest the radar will be mapped on the scope. Thus terrain features, especially those close to the radar, are often displayed but are sometimes distorted in shape and size. Only the side of a mountain facing the radar is detected, and intensities may vary in the display because of differing slope angles and terrain cover. Echoes from coastlines may be reflections from tree lines and high ground features and do not necessarily show the actual coastline shape.

3.2.2 GROUND CLUTTER

Terrain features such as hills, buildings, trees, and powerlines located very near the radar set may produce permanent or semipermanent echoes on the scope, depending on their distance, relative height, and the prevailing meteorological conditions. During periods of ducting and super-refraction the extent of this ground clutter is often greater than under normal conditions. Each radar has a characteristic ground clutter display around the center of the PPI, and each radar station should have recent photographs of the normal ground clutter as well as photographs of the ground clutter as seen during unusual propagation conditions. Also, each WBRR user should have photographs of the ground clutter from the parent radar to assist him in proper interpretation of the display (see fig. 15).

Table III

COMPARISON OF HYDROMETEORS*

PARTICLE	RADIUS	CONCENTRATION	TERMINAL FALL VELOCITY
Typical condensation nucleus	0.00001 cm	1,000,000/liter	.0001 cm/sec
Typical cloud drop	0.001 cm	1,000,000/liter	1 cm/sec
Large cloud drop	0.005 cm	1,000/liter	27 cm/sec
Borderline drop (cloud to rain)	0.01 cm		70 cm/sec
Typical raindrop	0.1 cm	1/liter	650 cm/sec

*B. J. Mason, Clouds, Rain, and Rainmaking (Cambridge, 1962), p. 76.

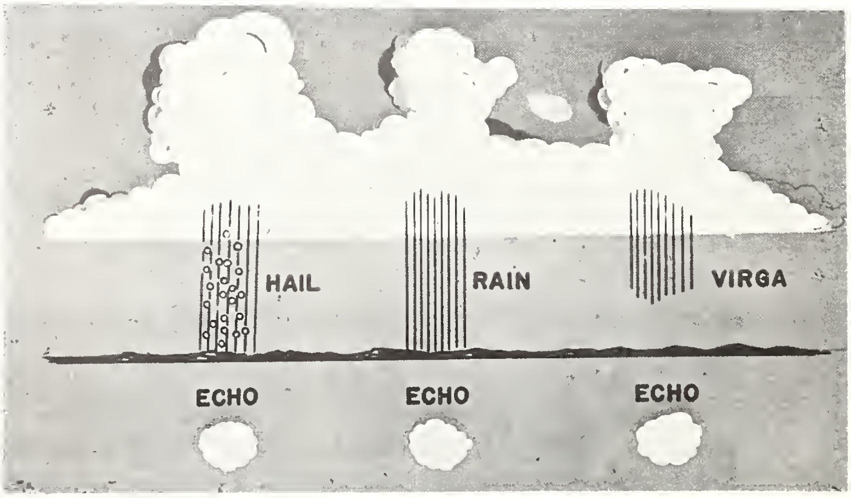

Figure 17. Weather Service radars do not normally detect cloud particles. As shown here, the weather echoes represent only those drops large enough to fall as precipitation.

3.2.3 METEOROLOGICAL TARGETS

Raindrops, cloud droplets, and other hydrometeors return radar energy to the antenna, and while there is but little energy returned from each of these small targets a concentration of the hydrometeors will produce a detectable echo. While it is convenient to consider radio energy returned to the radar from a target as having been reflected, this is not entirely accurate, especially in the case of targets small compared to the wavelength of the energy. The energy incident on the small particle causes an oscillation of the electric charge in the particle, and this in turn affects a radiation of energy by the particle at the wavelength of the incident radiation. In the field of radar meteorology, both this phenomena and true reflection are generally referred to as "scattering." The term "reflectivity" is often used to describe intensity of signal return by a target.

3.2.3.1 CLOUDS

Weather Service radars (10 cm) normally do not detect cloud droplets, showing rainshafts but not clouds (fig. 17). There are possible exceptions, especially at close ranges. However, many targets identified as clouds very likely consist of rain size drops that either evaporate before reaching the ground or are being suspended in updrafts.

Radars with a shorter wavelength are more likely to "see" cloud droplets, since received power is inversely proportional to the fourth power of the radar wavelength. For this reason, a powerful 3 cm radar, such as a CPS-9 (see Table I), may detect clouds more often than a 10-cm radar. Radars designed specifically as cloud detectors have wavelengths on the order of one centimeter. See figures 18 and 19.

3.2.3.2 RAIN

It is assumed that the WSR-57 detects all water drops of precipitable size, subject to range and power limitations. However, as a consequence of scattered energy being dependent on the sixth power of drop diameter, large drops will have a greater reflectivity than a greater concentration of smaller drops. This has turned out to be a rather fortunate circumstance for those wishing to estimate rainfall rate with radar intensity measurements, because it has been found that there is a relationship between drop size and rainfall rate. This makes radar a very useful tool for hydrology and local warning purposes. Furthermore, it has been found that the most severe turbulence in thunderstorms is usually associated with the strongest echo, and therefore radar is very useful to pilots and air traffic controllers.

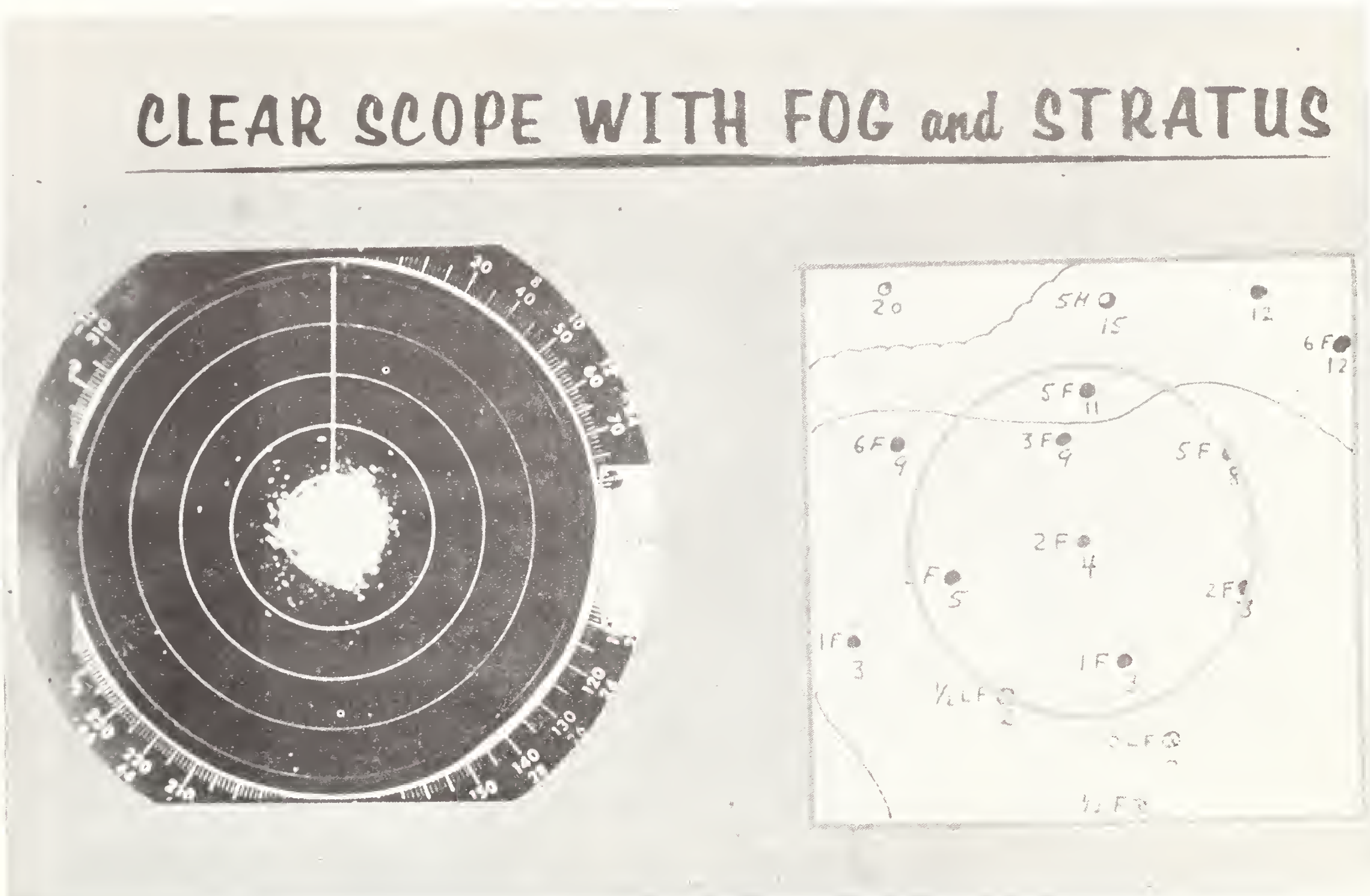

Figure 18. A radarscope free of echoes does not necessarily indicate clear weather. This scope shows only normal ground clutter and aircraft, although low ceilings and visibility prevail in the area. The fog and stratus droplets are too small to be detected by the radar.

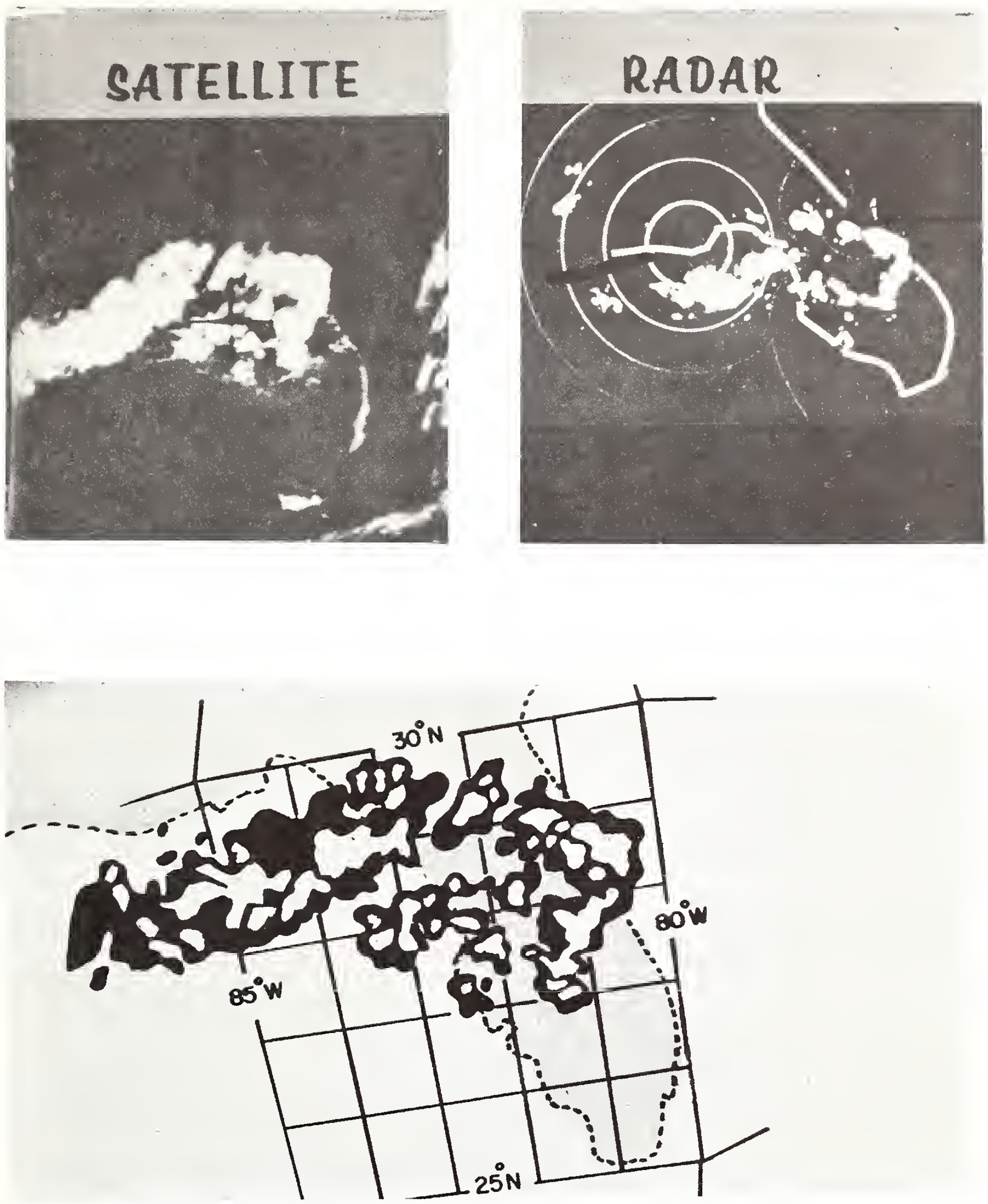

Figure 19. A weather system over Florida and the eastern Gulf of Mexico, as seen by satellite and by 10-cm radar. The upper left is a photo of the cloud system as seen by satellite, and the upper right is a composite photo of the rainfall, made from WSR-57 radars at Apalachicola and Daytona Beach. In the sketch below the two views are superimposed, the larger black areas being the satellite view, and the white cells in the black areas the radar view.

3.2.3.3 SNOW AND ICE

Since scattering by an ice crystal is about one-fifth as great as scattering by a water sphere of the same mass, radar echoes from snow are weaker than echoes from rain having an equivalent water content. However, ice with an outside coating of water, as is found during melting, will have a scattering coefficient near that of a water drop of the same diameter. Since this diameter is greater than that of a pure water drop of the same mass, reflectivity figures from water-coated ice can be very high. This, along with the large size of hailstones, is thought to account for the extremely high reflectivities sometimes found with hail, and to account for the "bright band" sometimes seen in more stable precipitation systems. The freezing level, or more accurately the melting level, is often observed by radar because as snow begins to melt it will have a coating of water, and its scattering efficiency will increase, making an enhanced echo on the scope. When completely melted the drop will be smaller and will have a greater fall speed, resulting in a lesser concentration of smaller drops and a consequent weaker signal at lower altitudes. The bright band is fairly common in the winter months, and is usually associated with synoptic scale weather features. It sometimes can be found in the decaying stages of large thunderstorms. A radar sweeping normally will of course not detect a bright band overhead, but will display echoes at those ranges where the beam intersects the melting snow. In the extreme case a relatively narrow echo will completely encircle the center of the PPI, with the circle diameter dependent on the freezing-level altitude. In order to comprehensively map an elevated echo such as this, it is necessary to sweep vertically with the antenna at numerous azimuth headings or to make small changes in the antenna tilt angle over several consecutive horizontal sweeps. Bright band RHI display is illustrated in figure 20.

3.2.4 REQUIRED STUDY

FMH No. 7, Part B, Paragraphs 3.4 and 3.7, and Chapter 5.

3.3 SYNOPTIC SCALE WEATHER SYSTEMS

Complete precipitation fields associated with synoptic scale systems are almost always too large to be detected and displayed by a single radar. Experience has shown, however, that we can usually infer much about the system from radar display. The different types of weather systems have characteristic radar "signatures," and by observing the variation in these signatures with time and distance, as shown by radar, we can make valid conclusions about the size, intensity, and movement of the systems (see figs. 21 through 25). By continually observing a large area, radar very quickly detects changes in precipitation intensity, coverage, and movement, that might take several hours to detect from the conventional observing network. Chapter 5, Part B, of FMH No. 7 gives more detailed descriptions of radar echoes in synoptic scale systems.

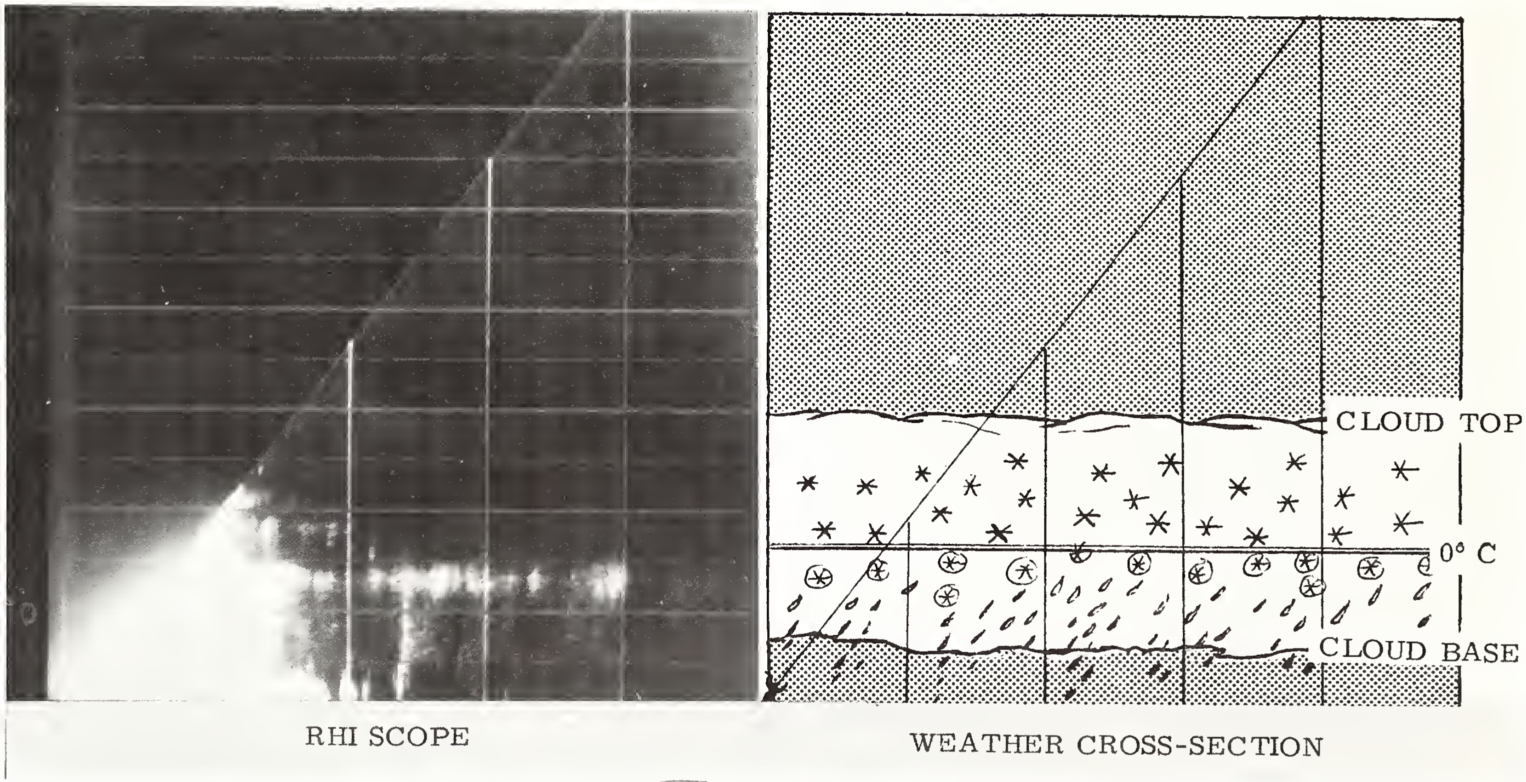

Figure 20. The drawing on the right illustrates the weather conditions that produced the RHI display seen on the left. The snow in the upper levels of the cloud was not detected by the radar, but as it fell into warmer regions and began to melt, it became water coated and had high reflectivity. When it became completely melted near the base of the cloud, its reflectivity decreased. The drops were small, and very little precipitation reached the ground.

3.3.1 WINTER CYCLONES

Cyclonic storms in the northern and central parts of the United States often exhibit a large, almost solid, mass of stratiform echo that shows some vertical development within about 150 miles of the low center. In some cases the echo mass breaks into showers along the cold front and cuts off rather abruptly in the cold air mass. The high-level cirrostratus and snow virga often seen far out ahead of an advancing winter cyclone are frequently detected by radar, and elevated echoes may be the first to appear on the scope as a winter storm approaches. Storms over southern states only infrequently exhibit the "standard" winter cyclone pattern. Figures 22 and 23 are PPI presentations rather typical of early phases of the approach of a winter cyclone.

3.3.2 SUMMER CYCLONES

Summer cyclones and low-altitude winter cyclones are more difficult to recognize than high-altitude winter cyclones because the echoes associated with the summer storms are normally convective and cellular in nature. Since the cyclone system is usually far too large to be viewed by a single radar, any single radar will generally display a field of scattered to broken echoes with a random, or at least difficult to recognize, pattern. Exceptions will be, echo lines associated with fronts and squall lines and large, fairly solid echo areas close to the center on northern sides of well organized summer cyclone systems. Movement of echoes associated with summer cyclones is usually relatively easy to measure because of their cellular nature, but care should be used in using this cell movement to infer cyclone motion. Very often a single radar cannot see enough of the echo field to identify field motion.

3.3.3 HURRICANES

Hurricanes are the most spectacular of the large scale echo patterns. A well-developed storm is recognizable even when the center of the storm is a great distance from the radar, and when the center gets close enough that the wall cloud is detected, the hurricane is usually unmistakable (fig. 24). The first echo indicators of hurricanes are not so easily recognized, however. Outer rain bands often appear well ahead of the large rain shield, and while they are curved in a large spiral shape, the radius of curvature is usually so great as to be difficult to recognize. These outer bands often contain squalls of greater severity than normally associated with tropical thunderstorms.

The eye of a well-developed hurricane is a very important feature, and its movement is sometimes easy to track by radar. It is necessary to be cautious in attempting to predict motion from such observations, because experience has shown that the eye does not advance at a steady pace, but rather has variations in both speed and direction. Eye paths have been known to zigzag, loop, stall, and even appear discontinuous, with the eye apparently collapsing and reforming at another location. The resultant track has short-term variations about the mean track of the hurricane, and these variations could be very misleading if used to extrapolate the position of the storm. The position and movement of hurricane centers, as stated by hurricane advisories and bulletins, result from the analysis of data from several sources and represent the best information available.

3.3.4 FRONTS

Precipitation associated with fronts does not always indicate the position of the front, as placed on weather maps, nor does it follow any set pattern. The widespread overrunning generally found with warm fronts often, but not always, produces a large smooth echo resembling somewhat the approach of a winter cyclone. As the front approaches, the base of high-level echoes gradually reaches the ground, and bands may appear in the larger echo near the surface position of the front. A bright band is commonly seen in the precipitation associated with a warm front. Radar is particularly useful in locating the thunderstorms occasionally imbedded in warm front weather, and operators should be alert to cores of high reflectivity in otherwise large formless echoes.

Cold fronts are even less inclined to radar signature than warm fronts. The echoes associated with cold fronts are usually cellular in nature, and not always arranged in lines along the front. Often when a line forms, it will not coincide with the surface position of the front, but the motion of any such line can often be associated with motion of the front. Radar is particularly useful in following the movement of precipitation associated with cold fronts, and in quickly detecting changes in precipitation patterns. The early detection of developing thunderstorms along a front, or developing squall lines out ahead of the front, can add important minutes or even hours to a warning service.

3.3.5 SQUALL LINES

Although squall lines are defined as "non-frontal" they often resemble a violent cold front, and are usually found in the warm air ahead of a cold front. They consist of a line of convective cells that can on occasion produce squalls, hail, or tornadoes. Squall lines vary considerably in length, from less than 100 miles to several hundred miles. Their large-scale motion is fairly conservative, but close inspection of the squall-line echoes usually will show that small-scale motion is irregular because of growth and decay of individual cells in the line. Sometimes the formation

of new cells is dramatic, with almost simultaneous appearance on the PPI of many cells in a completely new line near the old one. The old line will usually then deteriorate or merge with the new one, but on rare occasions the new development is short lived. Although there may be great variation in the appearance, intensity, and even position of a squall line, tracking a line by radar over several hours shows that the activity remains in an instability zone that has a fairly constant size and motion. Squall lines exist because of unusual instability, and therefore the change of the occurrance of severe weather increases tremendously in the squall line complex. Individual cells of high reflectivity or with unusual height, motion, or longevity, should be considered probable generators of hazardous conditions. Aircraft are particularly vulnerable to the extreme instability in and near squall lines, and should plan to give all parts of the line a wide margin of safety. When a squall line is on the scope it should be watched continuously for indications of severe weather. A rather large-scale development on squall lines that sometimes indicates severe weather is a wave, resembling the early stages of a wave along a frontal surface. This is called Line Echo Wave Pattern (LEWP) and is reported in the RAREP.

3.4 SEVERE LOCAL STORMS

Because weather radar views all points in its area of surveillance, it provides information on storms that might easily be missed because they lie between visual observation points, and it can easily provide information on size, shape, and changes in storms, that can seldom be determined from the visual observation network. Over most of the country, the network of weather observers is not sufficiently fine to view all weather occurrences, especially small-scale severe storms. By observing a radarscope we can usually determine not only the places where precipitation is occurring at any given time, but the intensity and movement of the precipitation and the characteristics of the weather system. Of major importance in interpreting radar display is continuity of observation. Observing an instantaneous display is much like viewing one frame of a movie film. You may be able to identify the characters, provided their faces are not turned from the camera, but you can't tell much about the action. In addition to closely watching the PPI, measurements of height and intensity are necessary to properly interpret echoes. Occasional sweeps at varying elevation angles and receiver gain settings, and vertical scanning of echoes, are important functions in observing weather by radar. This is especially true in the case of unstable weather situations that may lead to severe weather. Whenever thunderstorms appear on the scope the observer should give undivided attention to the radar and should become intimately acquainted with each echo, so that any changes are quickly noted. In general, the more intense the storm, as measured by reflectivity, height, and speed, the greater the chance of severe weather. Local severe storms sometimes present "signatures," by which they can be identified. Chapter 5, Part B of FMH No. 7 discusses these signatures in some detail, but we will give a brief description here. Be sure to note the summary of severe storm

criteria on page 5 - 24 of FMH No. 7. It should be well understood that although certain echo patterns have been identified in connection with severe weather, they are by no means infallible indicators.

Local severe storms have been noted in every season of the year, with single thunderstorms as well as with squall lines, and with nearly stationary thunderstorms as well as with rapidly moving ones. However, storms associated with intense squall lines or with a LEWP, or having extreme height or rapid speed, are particularly suspect. Rapidly moving thunderstorms are usually associated with sharp wind shifts and relatively high gusts at the surface, and depending on their reflectivity, with heavy rainfall and possible hail. Severe weather has been observed on several occasions near the junction of two thunderstorms. This junction is most common when one or both of the storms moves quite rapidly. When two storms approach one another, the wind shear that results can be quite large, due not only to the difference in their movements, but to the differing wind components in and near each storm. Time lapse film shows that many intense thunderstorms rotate about a vertical axis, as seen on the PPI.

The height of a storm relative to the height of the tropopause, appears to be a more important factor in the production of severe weather than the absolute height of the storm. Those storms that reach the height of the tropopause should be considered as probable producers of severe weather, and by the time they penetrate to 10,000 ft above the tropopause, a severe storm is likely occurring at the surface. Hail producing storms are found to be the highest in a given field. Thunderstorms with tornadoes nearly always penetrate the tropopause, often reaching over 50,000 ft. However, funnel clouds that sometimes reach the surface in southern Florida and around the Gulf of Mexico coastline often extend from cumulus clouds that have not reached the thunderstorm stage and are on the order of 20,000 ft in height. While these are not in the same class with the powerful midwestern tornadoes, they can cause local damage. Tornadoes are often associated with storms of high reflectivity, and in some cases the tornado itself may be highly reflective. The associated hook that has been observed on the radar PPI is found in the trailing half of the storm echo. Often the hook is masked in the large echo as seen by a powerful radar such as a WSR-57, but may become evident by adjustment of the attenuator control. Less powerful radars usually fail to detect the weaker echo around the hook, and present a picture of a hook extending from the main echo body even at full gain. Operators of WSR-1 and WSR-3 radars should be alert to the possibility of masked hooks, however, and should study suspicious storms at various gain settings. Tilting the antenna at various angles is also helpful, because sometimes the hook may appear aloft but not at the surface. Hooks have been observed to swirl from the parent cloud, and would appear to be associated with a micro-scale cyclonic circulation. The circle ascribed by the main part of the hook is usually from 4 to 12 miles in diameter. The surface position of the tornado is usually near the small end of the hook. Hook echoes are illustrated in figure 25. Although hooks

appear sometimes where there is no visual evidence of a tornado at the surface, their association with tornadoes is certainly strong enough to warrant immediate warnings when one is definitely identified on the scope. Be careful of "false hooks" which usually are short lived. Always keep in mind that the absence of a hook echo does not preclude the presence of a tornado.

Hailstones are highly reflective, and will generally produce an intense echo. This will appear as a hard core within a thunderstorm echo, or may extend as one or more "fingers" protruding from the edge of a thunderstorm echo. These fingers may be evident at full gain, or may appear only after the signal is attenuated. Vertical sweeps have produced, on the RHI, columns of high intensity that weaken near the ground. These possibly indicate hail that is melting before reaching the ground. Thunderstorms that produce hail are particularly violent, with intense updrafts and tops that usually penetrate the tropopause.

As discussed previously, stratiform precipitation presents a featureless echo, usually relatively large, that changes intensity and shape rather slowly and is not associated with violent weather. Such rainfall can cause flooding, however, and high reflectivity or lengthy sojourn over any watershed should be considered an indication of possible excess precipitation. One difficulty in dealing with large apparently stratiform echoes, is the possibility of overlooking imbedded cells of high reflectivity that indicate heavy rainfall, and may indicate localized convective activity particularly dangerous to aircraft because it is unexpected and hidden. While the turbulence associated with such cells is usually not severe, icing on aircraft can be very heavy in them because the vertical motion of the air suspends large quantities of moisture, both liquid and frozen. The heaviest icing will occur just above the level of the bright band that is often evident with stratiform precipitation.

3.5 ATTENUATION

Any process that reduces power density within the radar beam is called "attenuation," and for meteorological radar work range attenuation and atmospheric, or more commonly, precipitation attentuation are considered.

3.5.1 ATTENUATION BY PRECIPITATION

A certain amount of absorption occurs even in an atmosphere free of clouds and precipitation, but at frequencies used for weather radar this is negligible. Cloud droplets and precipitation may cause more severe attenuation, however, and must be taken into account.

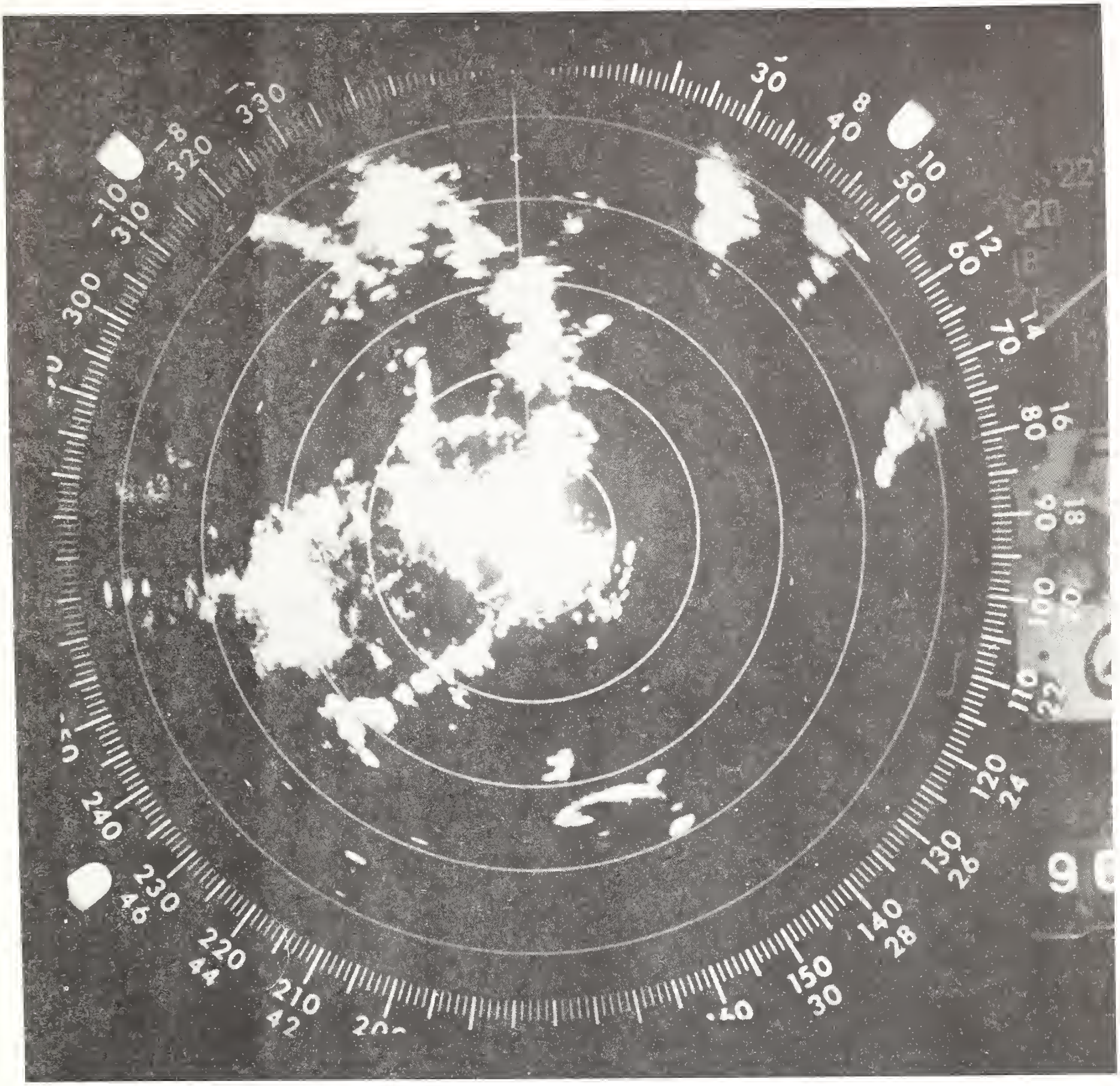

Figure 21. Typical PPI appearance of echoes from convective type rainfall. Note the irregular but generally sharply defined edges on the precipitation. Range marks are 20 nmi apart.

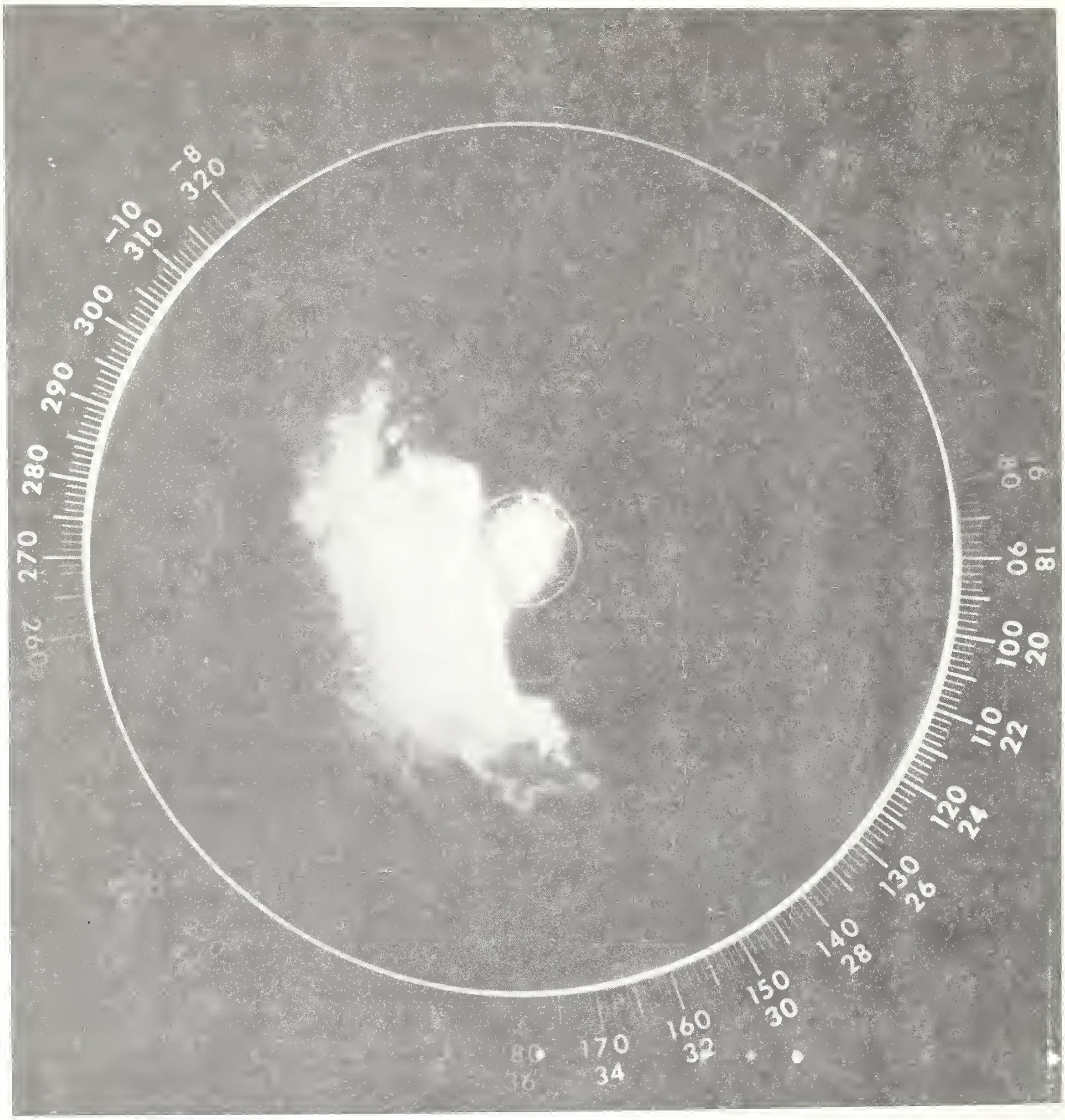

Figure 22. Typical PPI appearance of echoes from stratiform type rainfall. Note the maximum range of precipitation detection is roughly a semicircle. This may indicate that the area of rainfall is low level and extends to greater areal coverage than shown, but the radar beam is entirely above the rainfall at ranges beyond the edge of the semicircle. Range marks are 20 nmi apart.

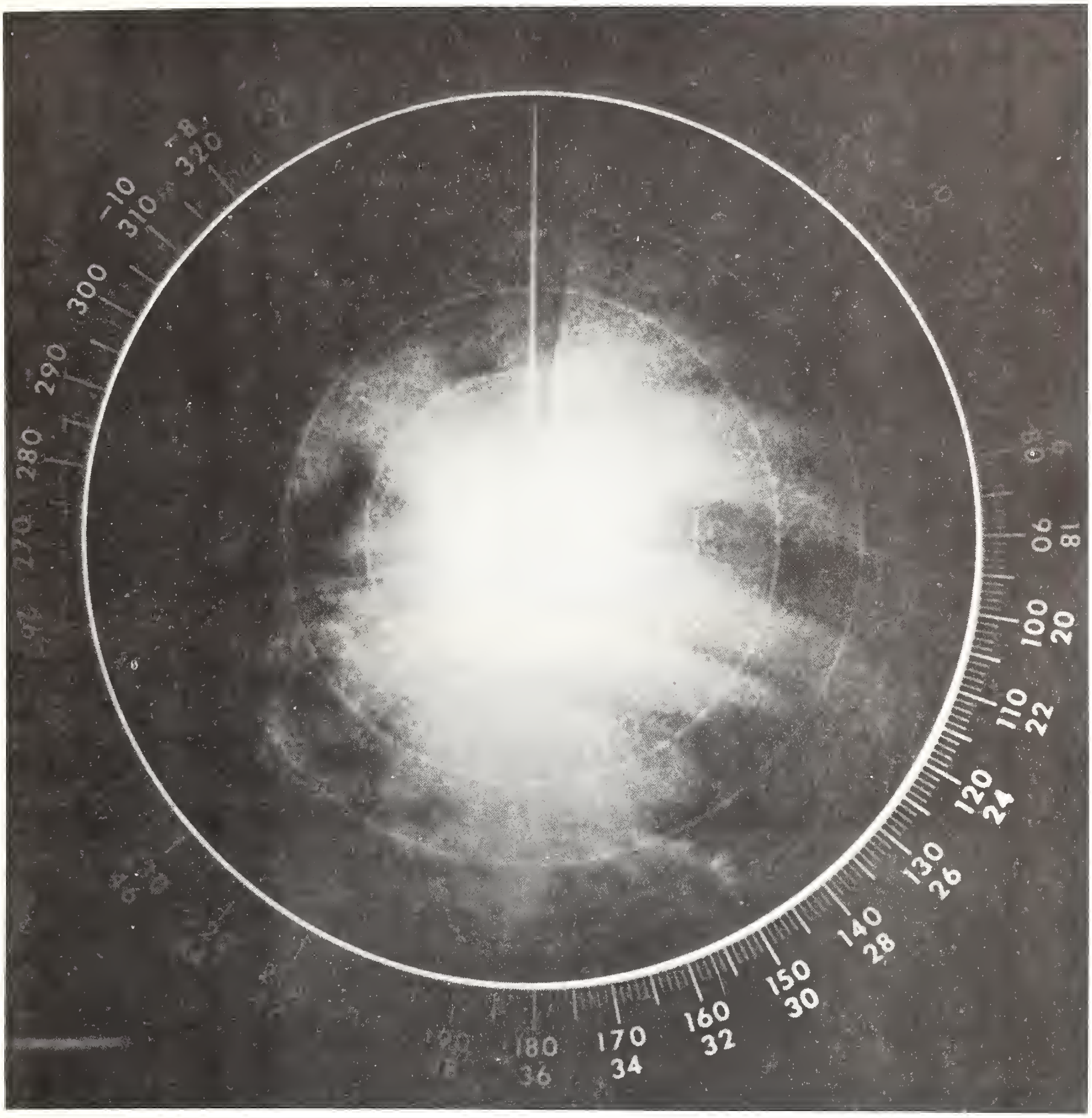

Figure 23. Typical PPI appearance of echoes from snow. Since reflectivity of snow is low, it may not be detected at great ranges. The area of falling snow is probably larger than shown on the scope. Range marks are 20 nmi apart.

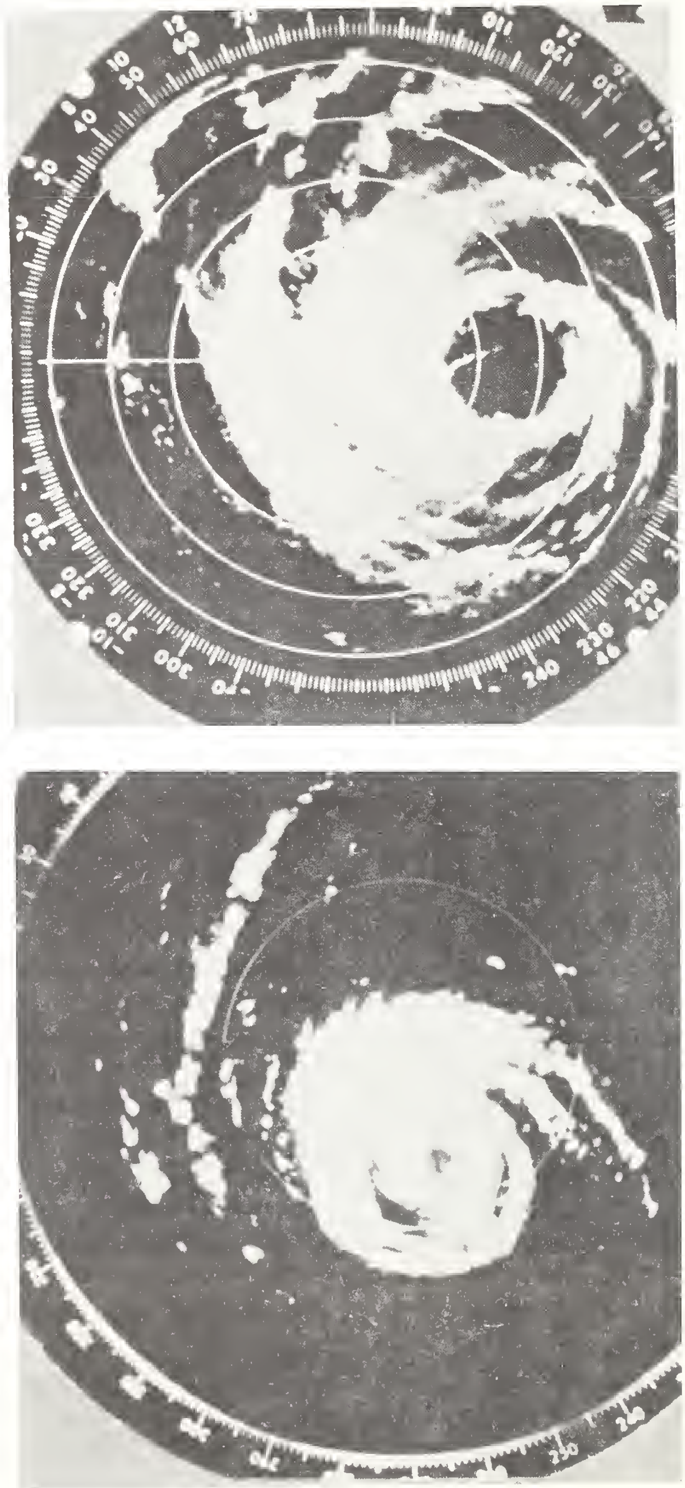

Figure 24. Typical hurricane echoes.

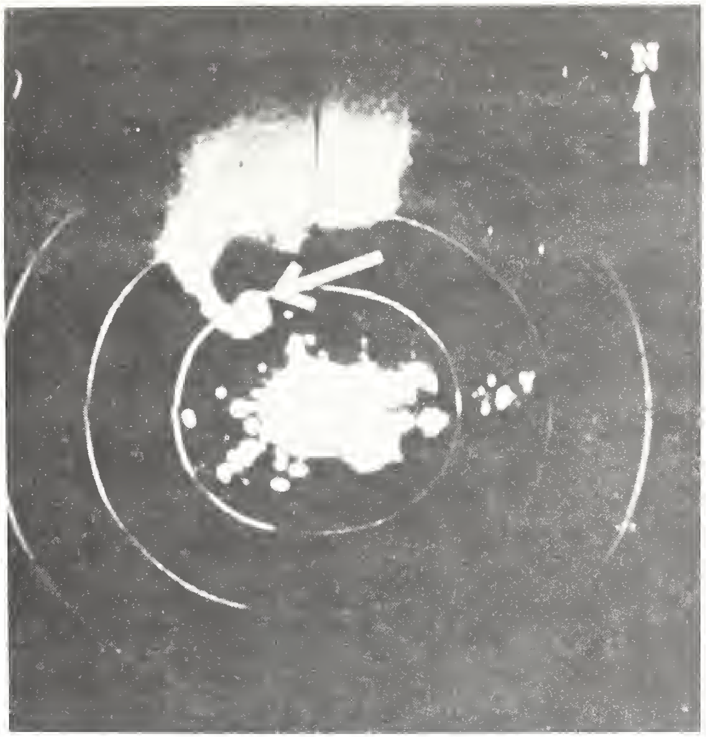

Figure 25. Hook-shaped echoes have been associated with tornadoes, the vortex being associated with the small end of the hook. This is not a foolproof indication of tornadoes, however, because irregularly shaped echoes will sometimes appear "hooked" when no tornado is present, and because not every tornado produces a hook on the scope. The radar observer has responsibility for determining if a hook echo represents a tornado. Hooks should be brought to his attention immediately because he may be momentarily away from the scope.

Attempts at quantitive measurements of atmospheric attenuation have been made, but these have no operational value at this time. In the operation of weather radar we can measure the difference in strength of the signal as transmitted and as returned from the target, but we do not know exactly how much of the signal strength depletion is due to target backscatter inefficiency and how much is due to attentuation between the target and the antenna. Unfortunately, a good target by its very nature is also an excellent attenuator, absorbing and scattering the radar energy in all directions. Attenuation, then, is like backscatter in that it is inversely proportional to the fourth power of the wavelength. The longer the wavelength the smaller the attenuation, if drop size distribution remains the same. This was an important consideration in selecting the wavelength of Weather Service radars. The relatively long 10 cm wavelength selected assures a minimum of attenuation by hydrometeors, and in the operation of these radars atmospheric attenuation is considered negligible although return from distant targets may be attenuated a slight but unknown amount by more nearby precipitation. In the case of radars with a shorter wavelength, a "V" shape indentation in the distant side of a heavy cell is a characteristic indicator of precipitation attenuation. Such an indicator may appear on the PPI of a low-powered 10-cm radar, such as a WSR-1, in the case of a large area of hail or extremely heavy rain (see fig. 27).

3.5.2 RANGE ATTENUATION

Range attenuation is the dissipation of radar beam intensity due to spreading of the beam. As the cross-section area of the radar beam increases with range, the beam energy is spread ever thinner, just as a flashlight beam becomes dimmer at greater distances from the flashlight. Figure 28 shows how a target might appear to the radar when at different ranges. Since the beam cross section has two dimensions, the energy falling on a point in the beam is proportional to $1/r^2$, where r is range.

Consider now how this affects weather surveillance radar. Since we make the very important assumption that meteorological targets completely fill the radar beam (fig. 29), all of the energy (assuming no atmospheric attenuation) transmitted by the radar is intercepted by the target, regardless of the beam cross-section area. Thus, all of the energy is scattered by the target, some of it in the direction of the antenna. But the antenna does not intercept all of the energy scattered by the target, and therefore the $1/r^2$ relationship must be applied to the backscattered energy. One can easily understand that the actual range correction applicable to each target would vary greatly if the targets only partly filled the beam. Our assumption that all meteorological targets fill the beam is a good one for most targets, as long as the top of the beam does not extend to an altitude greater than that of the target. This was a most important consideration in limiting routine intensity measurements to those echoes within 125 nmi of the radar (75 nmi for WSR-1 and WSR-3 radars).

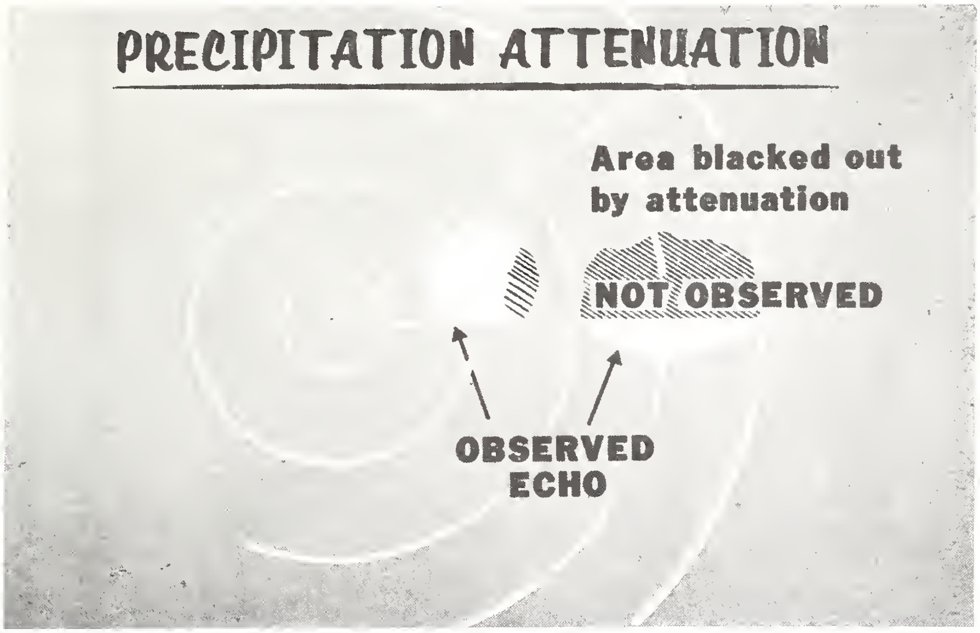

Figure 26. The nearby target absorbs and scatters so much of the outgoing and returning energy that the radar does not detect the distant target.

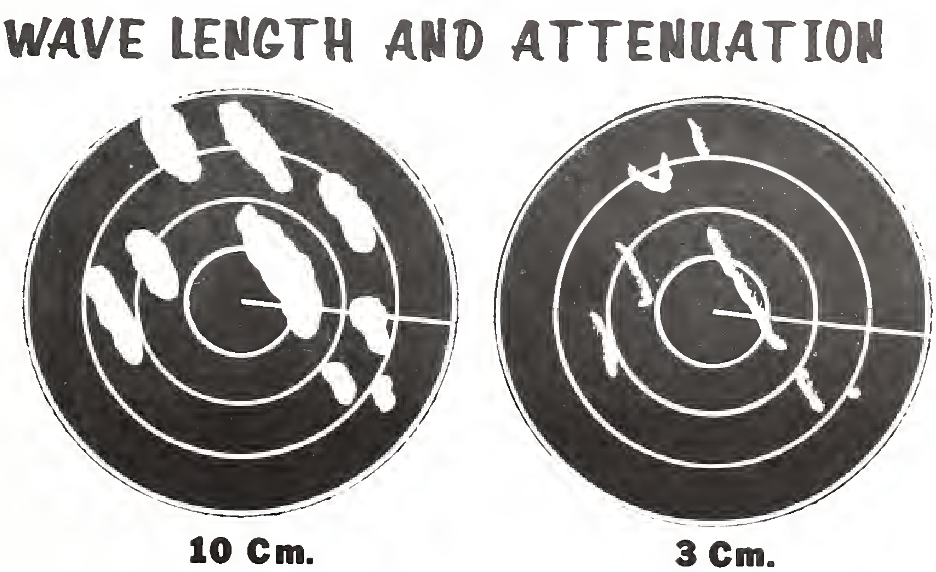

Figure 27. Weather targets as they might appear on radar sets with different wavelengths. Note the bright near edges and V notch shape of the attenuated echoes.

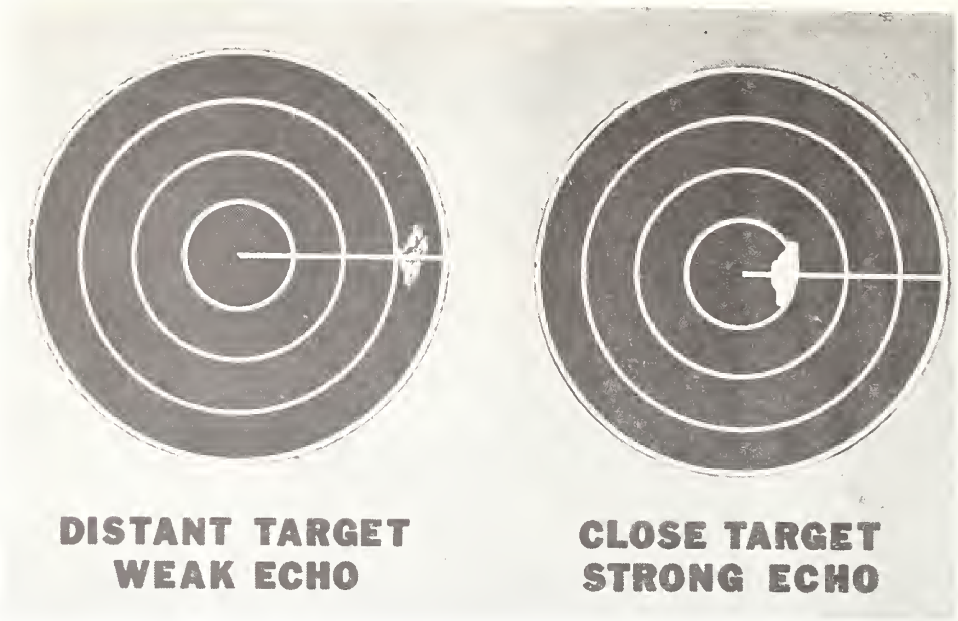

Figure 28. A rain cell as it might appear at different ranges. The difference in intensity is due to range attenuation.

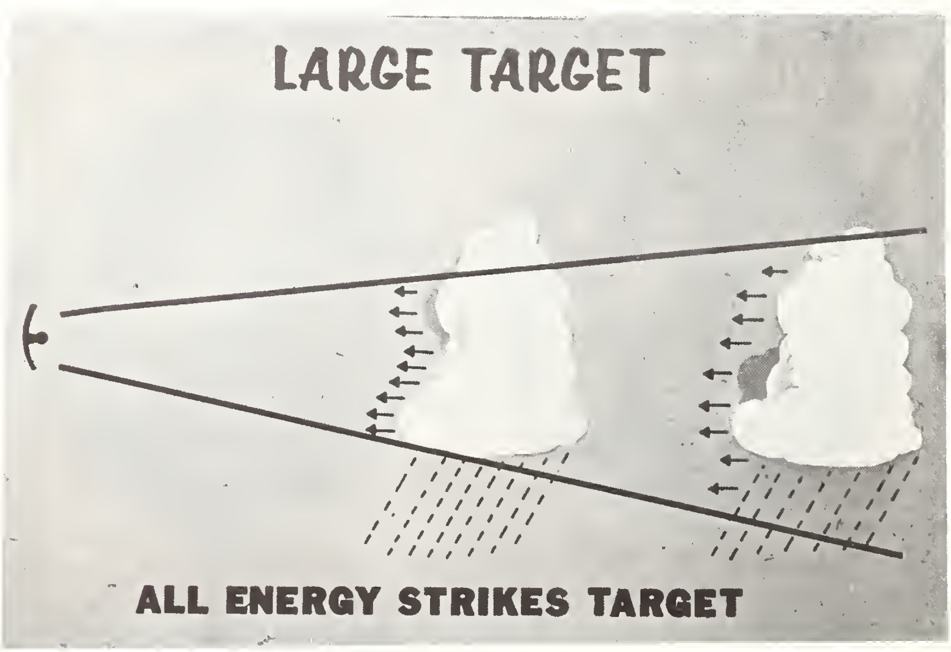

Figure 29. Precipitation targets that completely fill the beam receive total transmitted energy minus intervening attenuation, regardless of range.

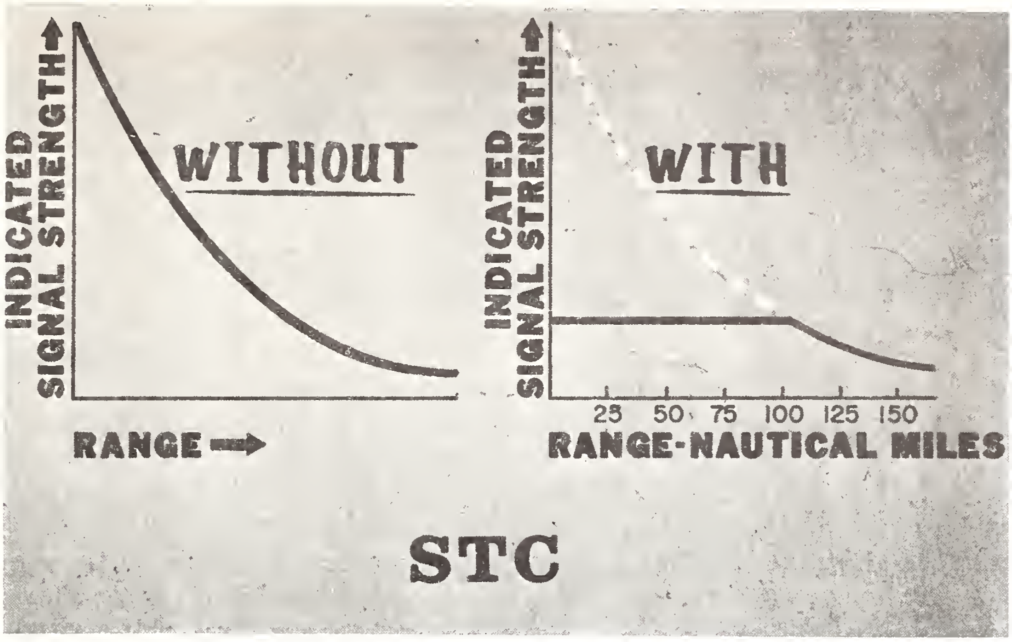

Figure 30. Range normalization compensates electronically for range attenuation.

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4. RADAR MEASUREMENTS AND REPORTS

4.1 MEASUREMENTS

Radar's usefulness as a tool to detect and describe precipitation over a wide area is due in large part to the objective information made available by the radar. Location, size, and movement comprise the basic information that first made radar attractive for weather observations. The addition of height and intensity data has, of course, greatly increased the value of radar weather reports. Subjective information based on operator judgment is also an important and necessary part of radar reports, but will not be considered in this section. We shall deal here with the objective information only.

4.1.1 DIRECTION

In order that echoes will be displayed on the PPI scope in their proper direction (azimuth) from the radar site, the PPI sweep line is synchronized with the antenna rotation. On both the console PPI and the WBRR display north direction is at the top, but the console display provides means for accurate direction measurements that are not available to the WBRR user. The azimuth ring associated with the PPI is graduated in one-degree increments and lighted to be always visible. The direction the antenna is pointing can be read at the end of the sweep line, and on the WSR-57, the direction of an arbitrary point on the scope can be read from a manually operated pointer. In addition, a number counter on the face of the WSR-57 console reads the direction, to the nearest degree to which the antenna is pointing. In the RAREP, directions are reported in whole degrees, relative to true north (see fig. 5).

4.1.2 DISTANCE

Radar energy travels at the speed of light, approximately 161,800 nmi/second. Since we can measure electronically the time elapsed between emission and reception of a pulse of energy, the distance it has traveled is easily computed. Distance between the antenna and reflecting target is, of course, half the total distance traveled by the pulse.

(161,800/2) (Number of seconds) = echo range in nautical miles.

Five evenly spaced range marks are displayed on the various radar scopes, their separation depending on the range being displayed. On the WSR-57, an electronic cursor associated with the A and R and PPI scopes can be manually moved to pinpoint the distance to arbitrary locations, the value being read to the nearest one-tenth mile from a number counter on the face of the console (see ¶2.2 - 2.4). Distances are reported in whole nautical miles, as measured from the antenna location.

4.1.3 MOVEMENT

Movement of radar weather echoes is measured by consideration of successive positions of the echo, or group of echoes. No effort is made to distinguish between translation and development, nor to associate the movement with any existing wind field. The radar observer simply acts as an umpire and "calls 'em as he sees 'em." He measures the distance and direction between two successive positions of the echo, reporting speed in knots and the direction from which the echo has moved. The reflection plotter mounted on the PPI of the WSR-57 greatly facilitates such measurements by minimizing the error of parallax and providing a measuring surface directly over the scope. The time increment between successive points is normally 15 minutes in the case of cells and small elements, and 1 hour in the case of lines and areas.

4.1.3.1 When plotting the successive position of cells, it is usual to select the center of the cell and measure the distance and direction between the positions occupied by the center at different times. This means that, in the case of a cell that is rapidly changing size or shape, the resultant movement of any side or edge of the cell may not be the same as that reported for the cell. A user should be aware that in determining such things as onset of rainfall at a particular location it may not be sufficient to make a simple extrapolation based on reported cell movement.

4.1.3.2 The movement of areas is also generally measured from centroid to centroid, although this is true to a somewhat lesser extent than in the case of cells. It is not always possible to determine the centroid of an area with any degree of certainty, because the area may be large enough to extend beyond scope range, or the radar beam may overshoot part of the rain area. In addition to determining the movement of the area as a whole, an attempt is made to measure the movement of the cells or elements which comprise the area. This information is reported directly after the area movement.

4.1.3.3 The movement of lines is defined as the component of motion perpendicular to the axis of the line, and is so reported. It is also important to report the movement of individual cells in the line, as indicated in figure 31, if such movement can be determined. This is especially true if the line and cell movements are considerably different. In the case of sharply curved lines, or of lines that are moving with different speeds along their length, the movement at two or more significant points will be reported.

MOVEMENT OF LINES

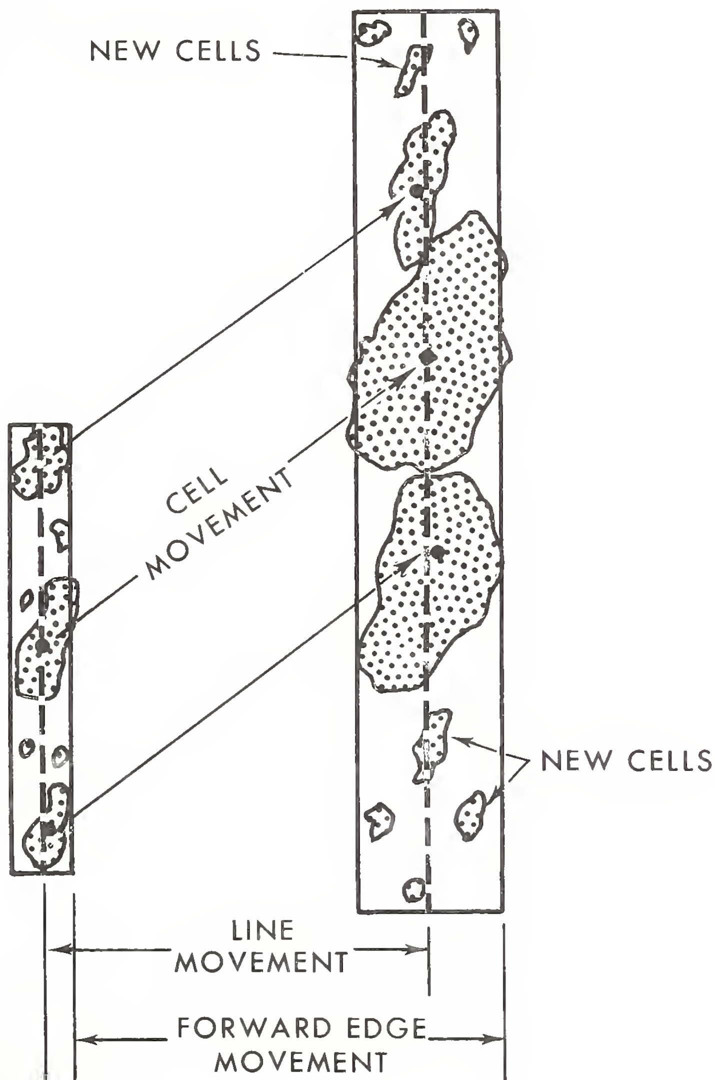


Figure 31. The reported movement of the line is the component of motion perpendicular to the line, measured center line to center line. Reporting both line motion and cell motion, along with growth and decay information, gives an accurate description of weather action. The line illustrated here has increased in width and length between observations.

4.1.4 ECHO HEIGHT

It is essentially a geometric problem to determine the height of an echo, since slant range and tilt angle can be easily measured. It is necessary to apply certain corrections to the geometric results, however, and these are discussed below.

ANTENNA HEIGHT. Since height reports refer to the heights above mean sea level, the height of the antenna above mean sea level is added to the geometric results.

EARTH CURVATURE. Earth curvature over radar ranges is of sufficient magnitude that a correction must be made for this curvature. Since the earth curves "downward" in relation to a straight-line tangent at the surface, the earth curvature correction is added to the geometric results.

ATMOSPHERIC REFRACTION. Refraction in the atmosphere causes the radar beam to curve in the same sense as the earth rather than travel in a straight line (see section 3.1). A straight line projected from the antenna is thus at a greater altitude than the actual radar beam, and it is necessary to subtract the refraction correction from the geometric results. The U. S. standard atmosphere is assumed for the purpose of this calculation.

BEAM WIDTH. The radar presents echoes on the scope as if the beam were a single line extending from the antenna. The beam is actually a narrow cone and its width at any point depends on the angular width of the beam and the distance from the antenna. In the case of the WSR-57, with a two-degree beam width, the beam has a cross sectional diameter of 21,000 ft at a range of 100 nmi. Any target just barely touched by the edge of the beam, that returns a detectable signal to the radar will therefore be displayed on the scope as if it were at the center of the beam -- an error of 10,500 ft. This error is, of course, less at shorter ranges and greater at longer ranges. If the radar operator tilts the antenna upward until he can just barely "see" the top of the target, the bottom edge of the beam is touching the target but the center of the beam is half a beam-width higher. Therefore, beam width correction is subtracted from the geometric result for determining echo tops. For finding the height of the base of those echoes that do not extend to the ground, the beam-width correction is added to the geometric result.

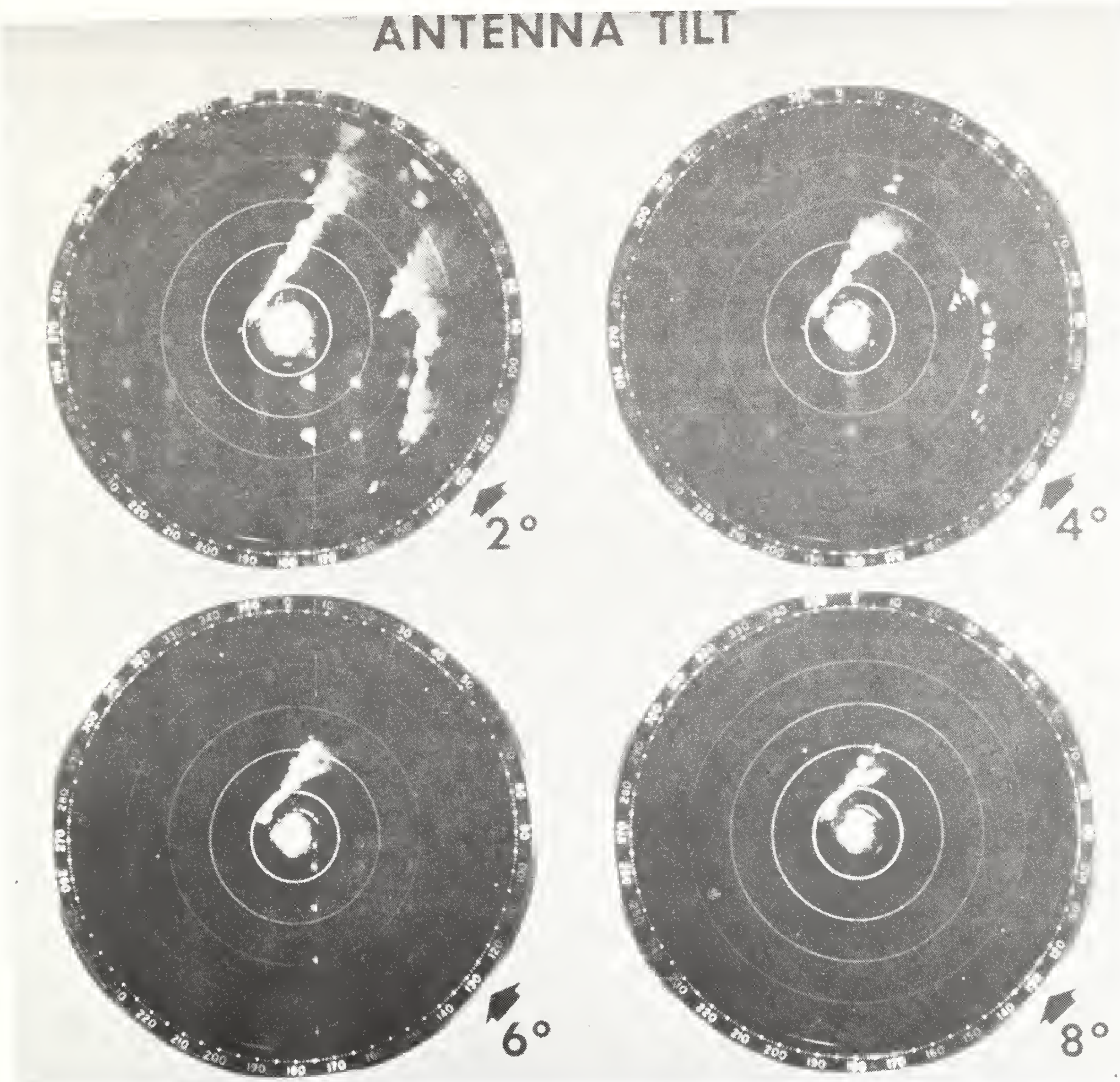


Figure 32. The radar views a different slice of the atmosphere when the antenna tilt angle is changed. These photographs were taken in a 2-minute period with the radar gain setting remaining constant. At an eight degree elevation angle the radar beam is overshooting all but the very nearby echoes.

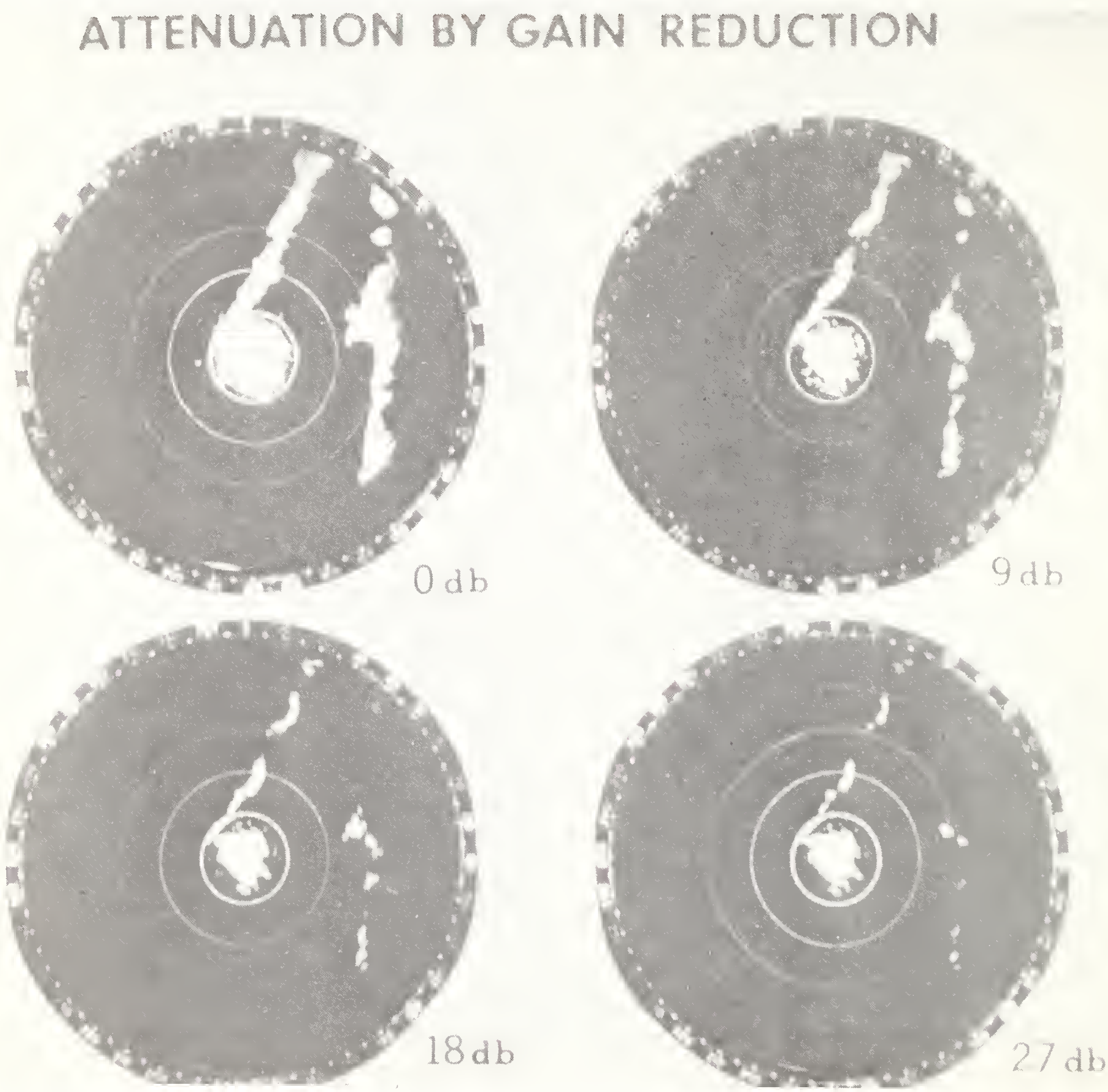


Figure 33. This is the same weather situation as shown in figure 32, but here the antenna tilt is held constant and the receiver gain is reduced in three steps. The "hard cores" of greater reflectivity are displayed when weaker parts of the echoes are blocked out by the step attenuators.

4.1.4.1 HEIGHT FINDING LIMITATIONS

A combination of these correction factors places a limitation on the effectiveness of the radar as a height finder at great ranges, and a practical range limit is established for each type of radar. The RHI on the WSR-57 has a maximum range of 125 nmi. In addition to the maximum range limitations, echo tops cannot be determined accurately at very close ranges, primarily because of antenna tilt limitations, extraneous echoes at very close ranges, and the necessity to add a component of the pulse length when the beam path through the echo has considerable vertical component. The WSR-57 has a minimum range for height determination of 5 nautical miles.

4.1.4.2 HEIGHT FINDING TECHNIQUE

The height of a target is usually determined by stopping the horizontal antenna rotation when the beam illuminates the target, and rotating the antenna vertically. On the WSR-57, the sweep line on the RHI scope will then rotate about the lower left corner of the scope and will paint a vertical cross section picture of the target. Height lines are marked on the scope in 5,000-ft increments to a height of 70,000 ft. Since the distance represented along the horizontal scale is much greater (125 nmi), echoes are considerably distorted, being stretched vertically (see fig. 8). The same distortion exists in the RHI display of the WSR-3 and WSR-4 radars, although the scope is different than that of the WSR-57. On the WSR-3 and WSR-4, RHI display is accomplished on the PPI scope by the use of a manual switch. Elevation angles are marked on the face of the scope, and the vertical sweep originates at the center of the scope, with the zero-degree elevation marker extending toward the 90-degree azimuth mark. Radars without RHI display can be used to determine height by noting the elevation angle of the beam at the top of the echo. Heights are reported in hundreds of feet above mean sea level, in 1,000-ft increments.

4.1.4.3 REQUIRED STUDY

FMH No. 7, Part B, Section 4.3.

4.1.5 INTENSITY OF ECHOES

Sophisticated electronics in modern weather radars make it possible to measure the strength of the received signal, and from this we can infer the intensity of reflectivity from the target. It is only one more step, then, to associate the intensity of reflectivity with intensity of rainfall. Many studies have been made comparing radar reflectivity with measured rainfall rates; and while there is some variability in the results all investigators develop equations of the same form, and when the various curves given by the equations are plotted together the majority fall in a narrow band. This encourages use to accept radar reflectivity from precipitation as a valid

measurement of the rainfall rate, and adds greatly to the usefulness of weather radar. While the results of radar rainfall rate measurements are variable about the rate as caught by a rain gage, for some considerations the radar measurements are possibly the most useful because they are made over a large area almost simultaneously, while rain gage measurements are point values.* It has been found that an overwhelming majority of the rainfall from any given rain system falls in the area of strong radar reflectivity, even though this area may represent only a small fraction of the total area of rainfall. Furthermore, there is a positive correlation between severe turbulence and strong radar echoes.

4.1.5.1 While we do not propose to develop the equation of signal power return and reflectivity here,† the signal power received by the radar (P_r) depends upon the characteristics of the radar (R_c) (i.e., power output, antenna gain, beam width, pulse length, and wavelength) the distance to the target (r), and the reflectivity of the target (Z). For those radars that have a wavelength shorter than 10 cm, atmospheric attenuation should also be considered. Disregarding attenuation, the power received is related to the other variable by:

$$P_r = \frac{R_c Z}{r^2}$$

Two important assumptions should be noted here. First, the Rayleigh scattering law is used, which states simply that the drops are spherical in shape and that their radius is not larger than about one-tenth the wavelength of the radar energy. This will be approximately true for rain drops, although it is known that their shape is not always spherical, especially in the case of the larger ones. Hail may exceed the 1-cm radius size limit (10 cm radar) in which case its reflectivity becomes great. The second and most important assumption is that the cross-section area of the radar beam is completely filled by the targets. Whenever the beam is not completely filled, the power received is reduced by a factor equal to that portion of the beam free of echo. This lends a range bias to intensity measurements, because the beam gets larger and higher as the range from the radar increases. For the WSR-57, a rain cell at 100 nmi must be some 20,000 ft in both vertical and horizontal size to completely fill the beam, and beyond that range the top of the beam

*McCallister, et al. "Operational Radar Rainfall Measurements," Twelfth Conference on Radar Meteorology, (1966), 208-215.

†See Appendix A.

overshoots many weather echoes. The beams of the WSR-1 and WSR-3 are twice as wide as that of the WSR-57, with the consequence that beam filling is a greater problem for these radars. Since we generally do not know what portion of the beam is filled, we can make no correction for this variable.

4.1.5.2 Inspection of the radar storm equation shows that there is an easily defined relationship between the target reflectivity and the power received by the radar, since the radar characteristics are constant and the range is easily measured. This leaves us with two problems; (1) defining the relationship between reflectivity (Z) and rainfall rate (R), and (2) measuring the signal strength received by the radar. We have already mentioned that the first of these problems is solved empirically.

The reflectivity varies with drop size and drop density, and consequently the various studies show a rough latitudinal and even seasonal variation. The value $Z = 200R^{1.6}$, with Z in mm^6/m^3 and R in mm/hr, is considered representative for a wide variety of rains, and is the value used in arriving at radar rainfall rates as measured by Weather Service radars. The second problem, measuring the signal strength received by the radar, is solved by varying receiver gain settings while viewing target representation on an A-scope. In the case of the older radars such as the WSR-3, not designed for objective intensity measurements, a method has been devised that allows classification of echoes into intensity categories with a fair degree of confidence. The WSR-57, along with other modern weather radars, has a greater dynamic range and precision attenuators, allowing for precise measurements over a wide range of intensities.

4.1.5.3 While the power transmitted by the radar is large, ranging from 60 kW for the WSR-3 to 410 kW for the WSR-57, the power received by the radar from the target is quite small and is, in fact, measured in terms of reference to a milliwatt (10^{-3} watt). We see that there is a factor of one million between the two. Definitions of signal attenuation or amplification are usually made by comparing one power level with another, using the decibel (dB) as the unit of comparison. The decibel can be defined as

$$dB = 10 \log \frac{P_2}{P_1}$$

where P_1 and P_2 are the two power levels. When one milliwatt is used as the reference power level, the term is

$$dBM = 10 \log \frac{\text{Power received (watts)}}{10^{-3} \text{ (watts)}}$$

If we substitute simple figures into the equation, we see that a signal with half the power of the reference (1/2 milliwatt) produces -3 dBm, and a signal that has 1/1000 the power of the milliwatt reference corresponds to -30 dBm, or is "30 dB below a milliwatt." The receiver in the WSR-57 normally detects signals down to 108 dB below a milliwatt (-108 dBm), which is very good sensitivity. The important feature is, of course, the calibrated attenuator stepping device which allows us to make a good measurement of signal strength. The received signal is attenuated in 3 dB steps, halving it each time, to a maximum of -99 dBm (WSR-57). The number of decibels necessary to decrease the signal amplitude to an established reference level is a measure of the power of the signal, hence a measure of the reflectivity of the target. This is converted to a rainfall intensity classification for reporting purposes. Figure 33 illustrates the change in the appearance of echoes as attenuation is applied to the echo signal.

4.1.5.4 The various intensity classifications, with their theoretical rainfall rate values, are shown in table IV, compared with surface observation reporting criteria. It is very important to note the differences between "radar intensity" and surface observation rainfall intensity criteria. The words used to describe the radar intensities actually refer to signal intensity rather than rainfall rate, but the symbols adopted for code purposes are those commonly used in reporting observed rainfall intensities. It should be noted that the symbols do not in all cases refer to the same values. It is important to keep this in mind when reviewing radar reports.

4.1.5.5 The choice of intensity to be reported for a single weather echo, such as a rain cell, is fairly obvious. The most intense return to be found from any part of the cell is considered to characterize the cell, and is so reported. The same reasoning is applied in the case of a group of convective echoes. The strongest cell in the group is considered to characterize the known potential of the cells in the group at the time of the observation. Convective cells often change their characteristics very rapidly, with the entire life cycle of individual cells possibly occurring between observations. Any group of convective cells likely contains, at any given time, cells ranging from new and increasing, through mature at maximum strength, to decaying and weak. With present day techniques it would be impossible to acquire any sort of meaningful median value by measuring individual cells in a group. Besides, our interest in such a case is not in the mean or average intensity to be found in the area, but rather in the intensity which represents the maximum potential of any cell in the group. For systems other than convective type, a category of intensity that is predominant throughout the area is more readily determined, and is used as the characteristic intensity. Intensities usually change less rapidly in stratiform systems and are more likely to be fairly uniform over large areas. Intensity measurements are not reported for frozen precipitation because a satisfactory reflectivity-

Table IV. Rainfall - Echo Intensities

<table>
<tr><th>Radar Observations</th><th>Rainfall Rate (In/Hr)</th><th>Surface Observations</th></tr>
<tr><td>Weak -</td><td><0.10</td><td rowspan="2">- Light</td></tr>
<tr><td rowspan="2">Moderate</td><td>Trace - 0.10</td></tr>
<tr><td>0.10 - 0.50</td><td rowspan="2">Moderate</td></tr>
<tr><td rowspan="2">Strong +</td><td>0.10 - 0.30</td></tr>
<tr><td>0.50 - 1.00</td><td rowspan="5">+ Heavy</td></tr>
<tr><td>Very Strong ++</td><td>1.00 - 2.00</td></tr>
<tr><td>Intense X</td><td>2.00 - 5.00</td></tr>
<tr><td>Extreme XX</td><td>>5.00</td></tr>
<tr><td></td><td>>0.30</td></tr>
</table>

snowfall relationship has not yet been developed. Intensity values are not reported for drizzle because some of the drizzle drops may be too small to be detected by radar, and because drizzle is usually confined to low levels where it may lie below the radar beam.

4.1.6 INTENSITY TREND

The intensity trend as reported in the RAREP is intended as an indicator of significant change. If the intensity of an echo changes by an amount approximately equal to, or greater than, the range of an intensity category (such as weak, which is approximately 16 dB at 125 nmi), the trend will be reported as increasing (+) or decreasing (-). If a change is less than a category range, it is reported as "no change." Note that with this definition it is possible for the intensity category to change from report to report, while the intensity trend is reported as "no change."

4.2 REPORTS

The radar operators at national network stations generally have two basic types of reports to make on a routine basis. One is the RAREP (Radar Report) designed for use mainly by Weather Service offices and the FAA (fig. 34), and the other is a narrative weather description designed for direct reporting by local news media and the FAA. Both should be available to remote display users, and should always be used to complement the remote display. Appendix B gives an example of a weather situation and associated RAREP and narrative reports. Another means of radar data dissemination is the transmission of maps of radar echoes via facsimile circuits.

4.2.1 RAREP (RADAR REPORT)

The RAREP includes all the weather echoes detected by the radar, supplemental information concerning severe or unusual conditions, notations of fine lines, and remarks concerning extraordinary phenomena. Weather echo information ordinarily includes type, configuration, amount, intensity, intensity trend, location, movement, height of echo tops, and height of bases, where applicable. The regular RAREP is completed once each hour, at H plus 35 minutes, provided there are weather echoes on the scope. Special observations are taken at other times when required. All weather echoes are grouped into one of four major forms (areas, lines, layers, and cells), and are described in accordance with the RAREP code. Lines and cells may appear within areas, and large precipitation areas may contain smaller areas of a significantly different type of echo (see fig. 35). The next few paragraphs discuss elements of the RAREP that are determined largely subjectively, and that have not been discussed previously in this chapter.

4.2.1.1 CELLS

When cells, either isolated or in a group, are reported individually, the report will include the type of precipitation, intensity, net intensity change during the 15 minutes just prior to reporting time, location of the center of the cell, movement of the cell when known (representing the 15-minute period just prior to reporting time), height of echo top if the echo is within 125 nmi of the antenna, size of the cell, and any pertinent qualifying remarks. If the cell intensity qualifies as very strong or greater its location will be determined by stopping the antenna rotation at a point where the sweep line illuminates the echo, placing an electronic cursor at the center of the echo, and then reading azimuth and distance from dial counters on the face of the radar console. Location then will be reported to the nearest whole degree of azimuth and to the nearest whole nautical mile in range. For cells of lesser intensity, a mechanical pointer over the PPI scope is used to determine direction, and distance is estimated with the aid of range marks. Direction in this case is reported to the

TA B-0-12
(Rev. 6-73)

CONDENSED EXPLANATION OF RAREP (SD) CODE

EFFECTIVE JUNE 1, 1973

LOCATION IDENTIFIER	TIME OF REPORT	CHARACTER OF ECHOES	WEATHER AND INTENSITY	INTENSITY TENDENCY	LOCATION AND DIMENSIONS OF ECHOES	MOVEMENT	ECHO TOPS	REMARKS
EVV	1640 Z	AREA 6	TRW + A	/+	4/125 221/115 100W	2715 CELLS 2325	MT 550 at 310/45	3/4 INCH HAIL 310/45

DECODED REPORT

Evansville Indiana hourly Radar Report (RAREP) taken at 1640Z. An area 6 tenths covered with echoes, containing thunderstorms producing heavy rainshowers and occasional hail at the surface. These echoes are increasing in intensity. Area extends from 4° 125 nautical miles to 221° 115 nautical miles, is 100 nautical miles wide. The area is moving from 270° at 15 knots, the cells within the area from 230° at 25 knots. Maximum top of the detectable moisture is 55,000 feet MSL at 310° 45 nautical miles. Hail ¾ inch in diameter was reported with this echo.

The above report is for the echo area in the radarscope picture. The slash mark (/) is used to separate the intensity of the echo from the intensity tendency.

TIME OF REPORT

Time of observation (24-hour clock) in Greenwich Mean Time. Observations are normally taken at 40 minutes past each hour. When a special observation is taken, the contraction SPL is placed between the Time of Report and Character of Echoes.

CHARACTER OF ECHOES

CHARACTER	DEFINITION	CONTRACTION
Isolated echo	Independent convective echo	CELL
Area	A grouping of related or similar echoes	AREA
Line	Related or similar echoes forming a line at least 30 miles long with a length-to-width ratio of at least 5 to 1	LN
Stratified elevated echo	Precipitation aloft	LYR
Spiral band area	Curved lines of echoes, including wall cloud, which occur in connection with hurricanes, tropical storms, and typhoons	SPRL BAND AREA
Fine line	Narrow, nonprecipitation echo associated with a meteorological discontinuity	FINE LN

NOTE: Echo coverage in tenths within an area, line or elevated echo is given by the number which immediately follows the word or contraction describing the character of the echoes. For example, AREA6 means that echoes cover 6 tenths of the outlined area.

PRECIPITATION SYMBOLS

IP	ICE PELLETS	SW	SNOW SHOWERS	ZR	FREEZING RAIN
L	DRIZZLE	T	THUNDERSTORMS	ZL	FREEZING DRIZZLE
RW	RAIN SHOWERS	S	SNOW		
R	RAIN	A	HAIL		

INTENSITY

LIGHT	−	VERY HEAVY	++	UNKNOWN	U
MODERATE	NO SIGN	INTENSE	X		
HEAVY	+	EXTREME	XX		

INTENSITY TREND

TREND	CONTRACTION
Increasing	+
Unchanging	NC
Decreasing	−
New	NEW

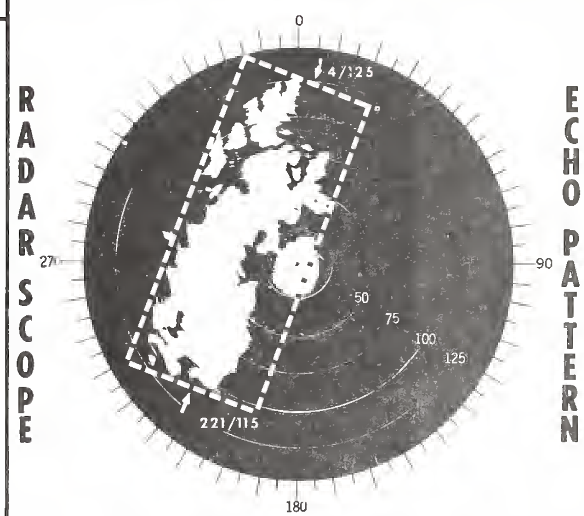
The intensity trend is evaluated in terms of a net change in the characteristic intensity equal to approximately one intensity category (light to moderate) during a specified time period, which is one hour for lines and areas and fifteen minutes for cells.

DIMENSIONS OF ECHOES

Width (W) or diameter (D) are reported in nautical miles. The average width of lines and rectangular areas, and the average diameter of cells and roughly circular areas, are reported.

MOVEMENT

Direction, to nearest ten degrees from which, and speed in knots with which, the echo is moving. Both cell and system movement are reported when available. Line movement is reported in terms of the component perpendicular to the axis.



LOCATION OF ECHOES

1. Locations of echoes are relative to the radar position. The azimuth in degrees true, and the distance in nautical miles, to salient points of the echoes are given.
2. If the echoes are arranged in a line, the azimuth and distance will be given to as many points along the axis of the line as are necessary to establish its shape.
3. If an irregularly shaped area is covered by echoes, the azimuth and range to salient points on the perimeter of the area will be reported as necessary to reconstruct the shape and size of the echo area.
4. If an area of echoes of roughly circular shape is observed, or if a single echo such as a thunderstorm cell is observed, the azimuth and range to the center of the area or cell will be reported.

ECHO TOPS

Maximum height of detectable moisture, in hundreds of feet above mean sea level. Tops are not reported beyond 125 nautical mile range.

UNUSUAL ECHO FORMATIONS

Certain types of severe storms produce distinctive patterns on the radar scope. For example, the hook-shaped echo associated with tornadoes and the spiral bands with hurricanes. The bright band is a narrow horizontal layer of intensified radar signal a short distance below the 0°C isotherm (Melting level). Unusual echo formations will be reported in remarks.

OPERATIONAL STATUS

STATUS	CONTRACTION
(1) Equipment performance normal on PPI scan; echoes not observed	PPINE
(2) Equipment out of service for preventive maintenance resulting in loss of PPI presentation. (The contraction is followed by a date-time group to indicate the estimated time when operation will be resumed.)	PPIOM
(3) Observation omitted for a reason other than those above, or not available	PPINA
(4) Radar not operating on RHI mode; echo altitude measurements not available	RHINO
(5) A-scope or A/R indicator not operating	ARNO
(6) Radar operating below performance standards	ROBEPS

A contraction pertaining to the operational status of the equipment is sent as required by the table above. In the above list, "PPI" refers to the radarscope (Plan Position Indicator); the additional letters refer to "no echo" (NE).

GENERAL NOTES

SD (Storm Detection)—Radar Report (RAREP) Identifier. Identifies the message as a RAREP.

When the report contains an important change in echo patterns, or some other special criteria given in the **Weather Radar Manual**, Part A has been met, it is designated as a special (SPL).

Intensity of precipitation at distances exceeding 125 nautical miles from a WSR-57 or other radar of similar sensitivity, or 75 miles from other radars, will be reported as unknown (U). Intensities of snow, hail, drizzle, and ice pellets are not reported.

One rainfall intensity category is selected to characterize each reported echo system. For convective systems, it is the maximum intensity in the system. For other systems, it is the intensity predominant in horizontal extent.

Persisting echoes are indicated in remarks.

U. S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL WEATHER SERVICE
SILVER SPRING, MD. 20910

Figure 34.

nearest whole degree of azimuth, as before, but range will generally be reported in increments of 5 nautical miles. Echo location on the PPI scope of the WSR-57 is greatly aided by a reflection plotter which is mounted over the scope. A grease pencil mark on the reflection plotter appears to have been made directly on the scope face, thereby avoiding parallax errors.

4.2.1.2 LINES

Lines are located by indicating end points, and any other points along the axis necessary to describe the shape of the line. The average width of the line is reported, with qualifying remarks where applicable. Areal coverage is reported to the nearest tenth part by the use of one or two digits directly after the configuration contraction. Example: LN8TRW etc... The intensity ascribed to the line is usually the greatest found in the line (characteristic intensity), because lines are ordinarily comprised of convective type precipitation. Intensity trend reported represents change in the maximum intensity during the 1 hour period preceding the observation time. The movement of a line is the component of motion perprendicular to the major axis of the line. That is, a line extending from north to south would be reported as moving only east or west. Line motion reported is representative of a period 1 hour prior to the reporting time. In addition to line motion, movement of individual cells in the line may be reported, and this cell motion will not necessarily be perpendicular to the major axis of the line. The cell motion is measured over a 15-minute period. The maximum echo altitude noted along the line will be reported as "MAX TOP," to the nearest thousand feet in hundreds of feet. Other tops may be reported when significant. All top reports use mean sea level as base.

4.2.1.3 AREAS

Weather echoes associated geographically and by physical causes are grouped and reported as "AREAS" in the RAREP. The location and size of an area are described in one of three ways: (1) by reporting the azimuth and range of the center of the area along with the diameter of the area, (2) by azimuth and range of end points of a line through the middle of the area, accompanied by area width, and (3) by the azimuth and range of significant points on the area boundary. In the latter case the points will be listed in order, clockwise around the area. Areal coverage is reported to the nearest tenth part by the use of one or two digits directly after the configuration contraction. Example: AREA8R- etc... If the area is composed of convective echoes, the maximum echo intensity noted in the area will be considered the characteristic intensity, and will be reported as area intensity. This does not mean that an isolated thunderstorm in a large area of light showers will necessarily establish the characteristic intensity of the area. If the radar observer considers isolated areas of cells as not characteristic of the whole area, he will report them separately.

If the area is composed of stratiform precipitation, the predominant intensity over the area will be reported as characteristic. Intensity tendency and area movement will represent a time increment of 1 hour, as with lines. Movement of cells or elements within the area may be reported separately, the time increment being 15 minutes. The highest echo top in the area will be reported, and other tops may be reported in remarks if thought significant.

4.2.1.4 LAYERS

The radar sometimes detects stratified echoes, the bases of which do not reach the ground. These are reported as layers (LYR), and position, shape, type, intensity, movement, and tops are reported as in the case of areas. In addition, the height of the base is reported in hundreds of feet. Layer thickness is sometimes difficult to determine because of beam width distortion, and in some cases information may be so nebulous that the layer is simply reported in remarks rather than in standard code format.

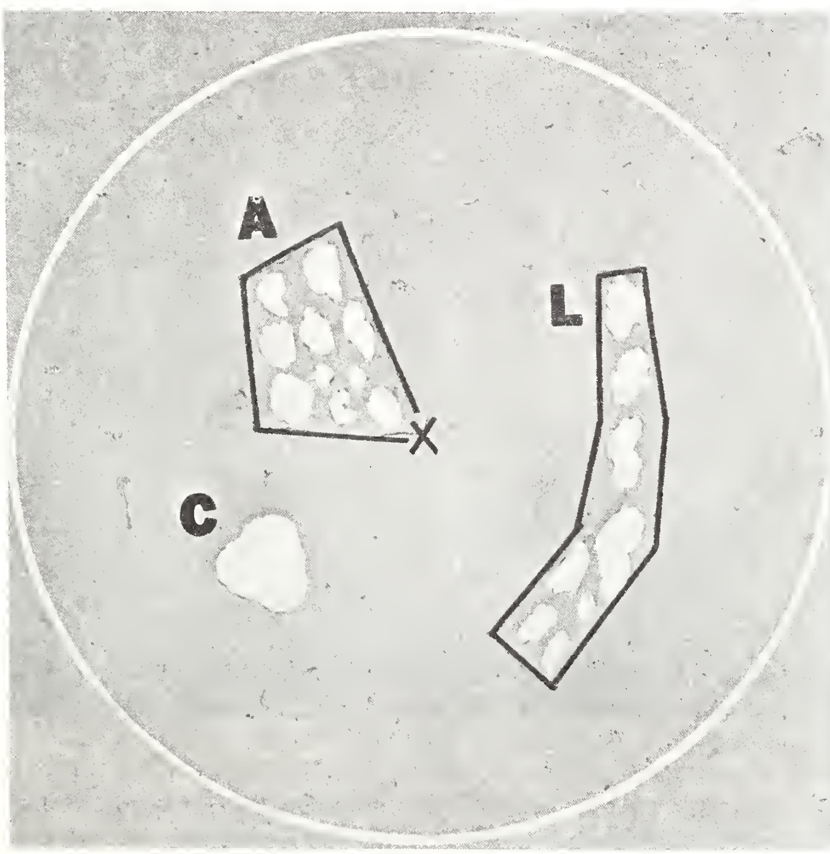


Figure 35. Grouping of echoes for reporting purposes. Classification involves, in addition to geographical location, consideration of configuration, coverage, continuity of pattern, and meteorological processes.

4.2.2 NARRATIVE RADAR WEATHER REPORTS

The narrative radar weather report produced at Weather Service radar stations is not intended for long-line distribution, and is tailored to meet the specific needs of the radar locale. Narrative reports are generally issued once each hour, but the frequency may vary with the time of day and the weather coverage and type. The report covers an area of assigned station responsibility, such as several counties, the area usually being about 200 miles across. Severe or particularly significant weather at greater ranges is often reported. Azimuth and range readings are not used to identify locations, but rather geographical and political features generally recognized by the public are used. Cities, towns, highways, state and county boundaries, rivers, lakes, mountain ranges, and coastlines, are typically mentioned as references in describing weather locations and movements. Acetate scope overlays showing these features are used at the radar site, and remote display users may desire a similar tool tailored to fit their display. Descriptions of weather types, intensities, and tendencies are usually not so specific as in the RAREP, with terms used in general public weather forecasts preferred. The radar observer must be constantly aware that his report will be delivered to the public as valid and timely until such time as he gets a subsequent report into the hands of the news media. For example, a thunderstorm may move 20 miles or more between regular hourly reports, and this may be significant in some localities. Unscheduled special reports are not necessarily effective unless flexible and highly effective communications, including necessary manpower, exist between the Weather Service office and the various news outlets.

The remote display user can gain a broader and more complete understanding of the scope display by reference to the narrative report as well as the RAREP. Generally speaking, the type of commerce and agriculture predominant in the radar surveillance area will be the same as the remote display user will be concerned with, so the emphasis in the report may be directly applicable to the use of the remote display user. However, user stations should be aware that with their observation and communication facilities they are uniquely fitted to provide the radar station with much needed verification and amplification information. Remote display users should be alert to necessary corrections and additions to both RAREP and narrative reports, and should bring these to the attention of the radar operator at the radar station.

4.3 REQUIRED STUDY

FMH No. 7, Part A, and Chapter 4, Part B.

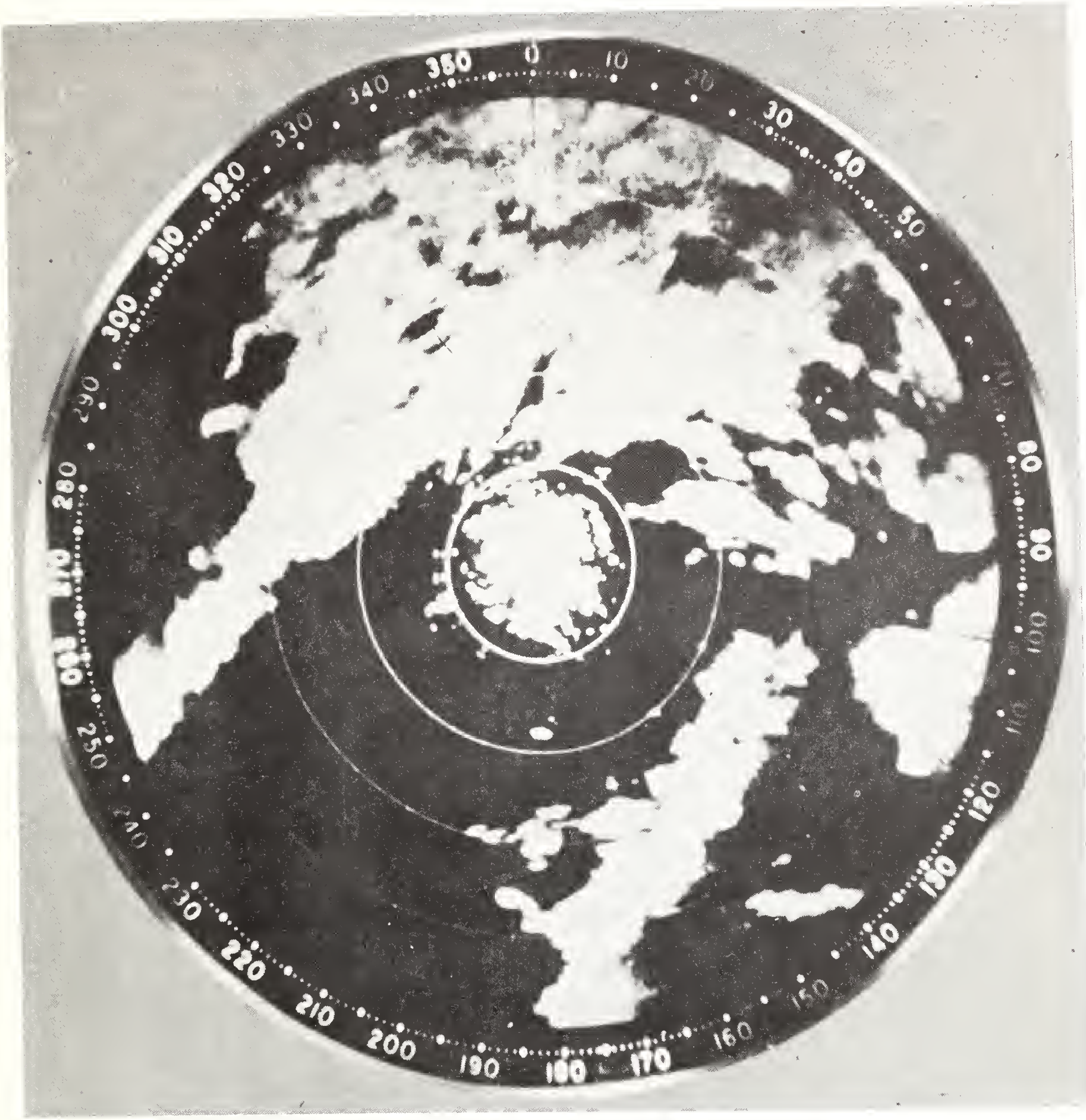


Figure 36. When the PPI display is the only information available, it is sometimes very difficult to identify and evluate the weather phenomena depicted. In order to evaluate such a PPI display as this one, the radar observer makes use of calibrated intensity attenuation, the A- and R-scope for ranging and character, and the RHI scope and angle tilt for vertical extent and configuration. He must use continuity considerations, and peruse all pertinent weather reports available.

Figure 37. Through the use of the data insertion device (DID) available on the WBRR, the radar observer can annotate the scope display that is transmitted, providing the user with readily available necessary information about the scope display. Shown here is the same scope picture as in figure 36, but with annotations that very greatly enhance the usefulness of the picture. Without this additional information the user could give only the geographical location of echoes and make only very gross estimates of their character and intensity.

APPENDIX A

RADAR ECHO INTENSITIES

The intensity assigned to a radar echo is determined by the radar observer employing an objective method based on an empirical relationship between radar reflectivity and rain intensity. In order that the user may make most effective use of these data it is necessary to have some idea of the physical principles involved. Basically, the radar transmits a very short burst of energy, then listens for that small portion of the energy backscattered from the target. The power received from the target is a function of the radar design parameters and the reflective qualities of the target. In the case of precipitation targets, it has been shown theoretically that the power which is backscattered to the radar antenna is proportional to the summation of the sixth power of the drop diameter. This is expressed mathmatically in the form: $Z = D^6$, where Z is radar reflectivity $mm^6 m^{-3}$.* The average power received by a radar system from a precipitation target is given by the following equation:

$$\bar{P}_r = \frac{P_t C Z}{r^2} \qquad (1)$$

This equation states that the average power received ($\bar{P}_r$) is directly proportional to the power transmitted (P_t), the radar constant (C) and the precipitation reflectivity (Z) and is inversely proportional to the square of the range (r). Included in the radar constant (C) are the radar design parameters such as antenna gain, vertical and horizontal beam width, pulse length, wavelength, and a term for the complex index of refraction.

Solving for radar reflectivity, equation (1) becomes:

$$Z = \frac{\bar{P}_r r^2}{P_t C} \qquad (2)$$

---

*mm - millimeter
m - meter

The final step is to relate the radar reflectivity derived from equation (2) to rainfall rate (R). Over the past 15 years, numerous studies have been conducted to establish the relationship of Z to R. Many factors are known to affect the Z-R relationship, such as drop size and type of precipitation. For example, a few large drops can produce reflectivity values as great or greater than many small droplets.

Equation (3) proposed by Marshall and Palmer is considered to be representative for most rains and is used by the National Weather Service.

$$Z = 200R^{1.60} \tag{3}$$

where Z is in mm^6/m^3 and R in mm/hr.

In the theoretical derivation of radar echo intensity a number of assumptions are necessary. It is not within the scope of this discussion to mention all of them, but we should point out the more important ones and how they may affect the interpretation of these data. In equation (1) the power received (P_r) is inversely proportional to the square of the range (r^2). This is an important assumption since it implies that the meteorological target completely fills the radar sampling volume. In actual practice the meteorological target does not always fill the beam, particularly at extended ranges (see fig. 3). The range attentuation factor in the radar equation for a point target would be $\frac{1}{r^4}$. Therefore, for a precipitation target, partially filling the radar beam might conceivably result in an attenuation factor of $\frac{1}{r^3}$ or some other variation of the exponent. The net result is generally an underestimation of echo intensity at extended ranges, particularly when the echoes are of limited vertical extent. Because of this intensity error at extended ranges, radar intensity measurements are not made at ranges beyond 125 nautical miles. Often the effects of overshooting or partial beam filling occur well within the 125-mile limitation; the user should be cognizant of reported storm heights and exercise his judgment accordingly. For example, winter storms approaching the west coast of California are often quite shallow, having tops to 12,000 or 16,000 feet resulting in a radar intensity classification of weak when in fact it may be moderate. While the Z-R relationship expressed in equation (3) is probably representative of most rains, it is based on assumptions which do not always occur in nature. For example, the target is assumed to be comprised of liquid, spherical rain drops of average size and distribution. Actually the sampled volume may be comprised of large flattened droplets or water coated ice spheroids or any combination of these. The reflectivity or scattering properties vary considerably with the precipitation state. Snow reflectivity is very complex and is not clearly established. Therefore, intensities from snow echoes are not determined and are reported in the RAREP with no intensity symbol.

In spite of these problems, the radar can and does give us a reasonably good estimate of storm intensity to a range of 125 nautical miles. The present method of classifying radar intensity in six categories (weak, moderate, strong, very strong, intense, and extreme) has been fairly well correlated with weather types and precipitation intensities.

Particular emphasis has been placed on the correlation of radar storm reflectivity with the occurrence of severe weather. Radar echoes reported in the "very strong" category correlate rather highly with the occurrence of thunderstorms, hail, and damaging winds.

The use of the radar intensity data often leads the user to some conclusions or assumptions that are not necessarily true. We should like to call your attention to them:

1. The radar intensity classifications, while related to theoretically derived rainfall rates, do not correspond directly with precipitation intensity reported in regular surface observations. The criteria for surface observations and radar are shown below:

SURFACE OBSERVATIONS

RW-	LIGHT	TRACE TO .1 IN/HR	RW-	LIGHT	LESS THAN .1 IN/HR
RW	MODERATE	.1 TO .3 IN/HR	RW	MODERATE	.1 TO .5 IN/HR
RW+	HEAVY	GREATER THAN .3 IN/HR	RW+	HEAVY	.5 TO 1.0 IN/HR
			RW++	VERY HEAVY	1.0 TO 2.0 IN/HR
			RWX	INTENSE	2.0 TO 5.0 IN/HR
			RWXX	EXTREME	GREATER THAN 5.0 IN/HR

2. The probability that the radar intensity will correspond with rain-gage data directly under a given echo is not high. There are several reasons for this: (1) The radar beam is sampling at some distance above ground level. Due to fall velocity, coalescence, trajectory, and evaporation, there can be quite a difference between the radar estimation and the precipitation caught at ground level. (2) The radar estimate is an instantaneous reading and is integrated over a large sample volume while the rain gage samples about a square foot over many hours.

In summary, radar can provide an estimate of storm intensity, based on theoretical and empirical relationships, in six categories, operationally useful to the user. Recent work by researchers show that point rainfall estimates are within a factor of 2 when compared to rain gage measurements. Hopefully the day will come when radar will provide precise rainfall measurements; however, at present a more realistic view is to use radar to augment rain gage networks.

APPENDIX B

REPORTING A TYPICAL WEATHER SITUATION

SITUATION:

The Florida Peninsula and the shallow waters north of the Keys are covered with scattered convective echoes. Some of the echoes over land have been attaining moderate intensity during the past 2 hours, but they have remained relatively small and there have been no reports of thunder. The echoes over water are generally smaller in diameter and height, and none have been observed to reach moderate intensity. Although the life span of individual echoes is less than 1 hour, the outline of the area covered has not changed significantly in either size or location during the past hour. Movement of representative cells, checked over a 15-minute period, is from 120 degrees at 11 knots. Some of the echoes south of Lake Okeechobee have increased in size, height, and reflectivity during the past hour, and some of them are now strong. The larger cells move from 250 degrees at 13 knots, but tend to dissipate as they move the east of the lake. New cells form and grow rapidly as the old ones move out. The result is that the area covered by the stronger cells remains in about the same location.

EXPLANATION:

1. The strong echoes are reported first because they are considered the most important (FMH No. 7, Part A, ¶5.2.2).

2. The rectangular area that incloses the strong echoes as well as closely associated cells that are not necessarily strong, is judged to have .6 of its area covered by echoes, hence the system and coverage are reported as "AREA6" (FMH No. 7, Part A, ¶5.2 and 5.3).

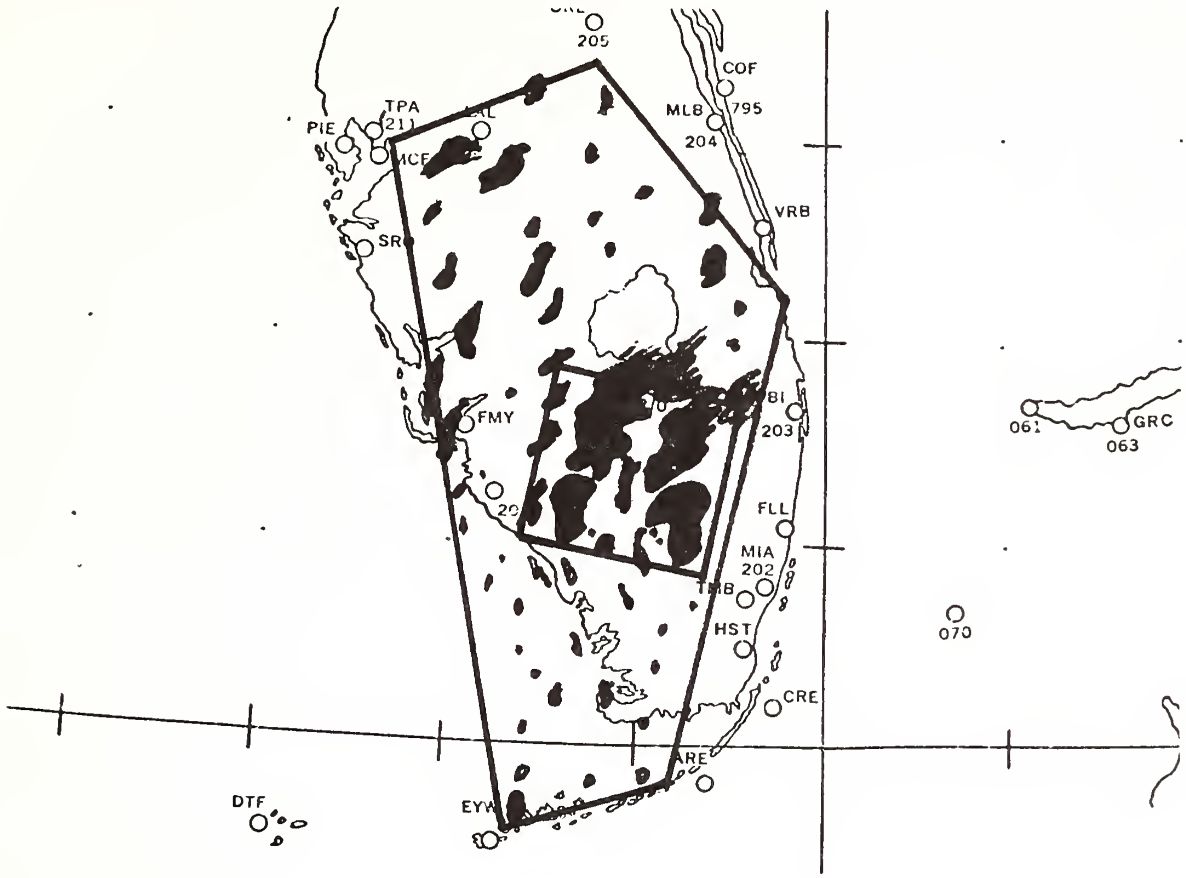
3. The intensity, shape, and size of some of the cells in the rectangular area indicate they are thunderstorms (FMH No. 7, Part A, ¶5.4.1, 5.5, and 5.6). Although not all the cells in the area are strong, the character and intensity of the strongest echo in the area are reported as the characteristics of the area. Since the intensity has increased by more than one intensity category during the past hour, the intensity trend is reported as increasing (FMH No. 7, Part A, ¶5.6).

4. End points and width of the rectangle are reported as the most economical means of describing the area (FMH No. 7, Part A, ¶6.1 and 6.5).

5. Since the rectangular area is greater than 50 miles in extent, the location of the maximum top height is reported (FMH No. 7, Part A, ¶8.3).

6. The moderate and weak cells comprise a system of echoes probably related by meteorological processes, and can be outlined by a fairly simple irregular shape (FMH No. 7, Part A, ¶6.1, 6.2 and 6.6). It is not necessary to make a note of the fact that the area of strong echoes is entirely enclosed by the area of moderate and weak echoes (FMH No. 7, Part A, ¶5.2.1). The echoes over the water could, of course, be reported separately as another area, since their characteristics are somewhat different, but in this case the information can easily be conveyed by a remark (FMH No. 7, Part A, ¶9.1). The northernmost defining point is reported first and the others are reported in clockwise order.

7. The maximum top was determined to be 28,000 ft, and other increasing tops over land are nearing that figure (FMH No. 7, Part A, Section 8).



RAREP:

MIA 1735 AREA6TRW+/+ 337/65 282/50 60W 0000 CELLS 2513 MT 430 AT 320/69
AREA2RW/NC 341/165 6/70 212/70 231/110 321/175 0000 CELLS 1211
MT 280 AT 294/87 CELLS OVR WATER ALL WK WITH TOPS BLO 200

NARRATIVE REPORT:

MIAMI WEATHER SERVICE Ø61255E

AT ONE PM THE MIAMI RADAR SHOWED A WIDE BAND OF THUNDERSHOWERS EXTENDING FROM THE SOUTHERN TIP OF LAKE OKEECHOBEE SOUTHWARD TO NEAR THE TAMIAMI TRAIL AND SOUTHWESTWARD TO WITHIN TWENTY MILES OF EVERGLADES CITY. ALTHOUGH THE ATLANTIC COAST WAS FREE OF PRECIPITATION SMALL SCATTERED SHOWERS CONTINUED OVER THE REST OF SOUTH FLORIDA AND ACROSS FLORIDA BAY TO THE KEYS.

Figure 38.